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REFERENCE

Lane, B. H., 1935, Suggestions to authors of papers submitted for publication by the United States Geological Survey: U. S. Geol. Survey, Washington, D. C. (For sale by Superintendent of Documents, Washington, D. C. 35c.)

ERRATUM

By a printer's error, line 1 on page 251, in Richard Foster Flint's paper entitled "Rates of Advance and Retreat of the Margin of the Late-Wisconsin Ice Sheet" in the May 1955 issue of the American Journal of Science, was omitted in the final printing. This page should begin: Retreat from the outer limit of advance in Ohio began less than 18,000 C^{14} yr. ago.

[American Journal of Science, Vol. 253, August 1955, Pp. 433-461]

American Journal of Science

AUGUST 1955

ZIRCONS IN ROCKS
1 SEDIMENTARY ROCKS

ARIE POLDERVAART

ABSTRACT. This is the first of a series of three contributions dealing with zircons in rocks. The present paper describes the size and shape distribution of zircons in sediments. Methods of concentration of zircons in crushed rock samples are summarized and methods of measurement of zircons discussed. Zircon has been shown to be a highly resistant mineral in sedimentary processes. Its relative stability in the sedimentary cycle is attributed to its resistance to chemical attack, small size, and lack of cleavage. However, there is evidence that alkaline solutions may corrode zircons. Minute zircon fragments are probably dissolved and complex zirconium anions may then be adsorbed, e.g. on hydrated ferric oxides. Thus it is believed that in shales only part of the total zirconium is present as zircon, while in oceanic clays zircon accounts for only a small proportion of total zirconium.

In sedimentary transport or upon reworking of sediments, zircons are repeatedly rounded, broken, and again rounded. In sandstones the majority of zircons are well-rounded grains, and both sharply euhedral crystals and angular fragments are usually in the minority. In siltstones increased proportions of broken grains are encountered. In shales the majority of zircons are angular fragments and rounded grains are in the minority. Generally sharply terminated, euhedral zircons are subordinate in sediments, and those present are small rather than large. Another general observation is that the average elongation ratio of sedimentary zircons is less than 2.0. A third general rule is that the average size of zircons decreases from arenites to lutites. Exceptions to all three generalizations may be found.

The stability of malacons is not as high as that of clear zircon. Accordingly, sandstones and siltstones contain few malacons, but considerable proportions of the zircons of shales may be gray, brown, or black. Possibly formation of malacon is promoted in minute grains by solutions present in shales.

Studies of zircon size and shape distribution in sediments are usually not particularly useful in paleogeographic investigations; as a rule variations in size and shape are minor, even when traced over large distances. Pronounced changes indicate different sources of sediments. The relative proportions of heavy nonopaque minerals are generally more revealing in sedimentary petrographic studies.

Finally, a few selected examples are given to illustrate the role of zircon in sediments; (1) Kalahari sands of the Bechuanaland Protectorate, (2) arenites of the Cape system, Cape Province, Union of South Africa, (3) Permian arenites of New Mexico, Oklahoma, and Texas, and (4) miscellaneous zircon studies given in the literature.

INTRODUCTION

Accessory minerals of sedimentary, igneous, and metamorphic rocks have held the interest of geologists for a long time, and a voluminous literature on the subject has accumulated. Zircon was singled out at an early stage as the mineral of greatest interest among the accessories. It is the most abundant, indeed practically ubiquitous, in rocks most suitable for study of accessory minerals, i.e. silicic and intermediate igneous rocks, arenaceous sediments, and their metamorphic equivalents such as quartzites, gneisses, and granulites. In addition certain special qualities were ascribed to zircon,

such as its being one of the least refractory minerals and most resistant to chemical weathering and abrasion.

The early studies were generally qualitative and not always objective.[1] This soon resulted in pronounced differences of opinion which eventually caused doubts regarding the hardy qualities ascribed to zircon, the validity of conclusions based on this type of work, and finally even the significance of zircon studies. This situation has persisted more or less to the present time. Good reviews of the literature are given by Reed (1937) and Hoppe (1951).

The introduction of statistical methods in petrology made it possible to place studies of accessory minerals on a semi-quantitative footing. For zircon, the relative abundance, color, habit, dimensions, elongation ratio, degree of rounding, and other properties can now be determined on a rough quantitative basis for each rock, and the resulting data compared with those of another rock or suite of rocks. Such positive expressions of zircon properties can replace vague and unconvincing statements concerning the prevalence of particular peculiarities of zircons which supposedly characterize a rock or a series of rocks.

The aim of the present contributions is to outline methods in statistical zircon studies, to indicate their significance to understanding of petrogenetic processes, and to stimulate further detailed studies in this field. This will be done in part by reference to such studies in the literature, and in part by the use of selected examples studied by the writer and others in the United States and South Africa. In turn will be discussed: (1) zircons in sediments, (2) zircons in igneous rocks, and (3) zircons in metamorphic rocks. Portions of these papers are admittedly speculative, but it is hoped that those who disagree will be provoked to provide data from zircon studies, rather than arguments, to disprove these speculations.

ACKNOWLEDGMENTS

In 1947 the writer initiated his long term program of zircon studies mainly as a result of Read's provocative series of addresses on the subject of granite (1939; 1943; 1944; 1946; 1948a; 1948b; 1949; 1951; 1955), Smithson's interesting investigations of sediments in England using semi-quantitative methods of study of accessory minerals (1939; 1941; 1942), and Coetzee's applications of Smithson's techniques in his study of Archaean metamorphic rocks of the Orange River valley in South Africa (1942a; 1942b). Throughout the years these studies were pursued as by-products of other researches, first at the University of Cape Town, South Africa, next at the Geological Survey, Lobatsi, Bechuanaland Protectorate, and finally at

[1] Starting with the work of Thürach (1884), a large number of zircon studies have been published. However, methods of concentration used often resulted in the loss of the smaller zircons and malacons. After the introduction of statistical methods in petrology (Niggli, 1924), zircon studies also became less qualitative (e.g. Zerndt, 1927; Wasserstein, 1933). However, the emphasis of these studies was on crystal habit of zircons (thereby largely eliminating rounded zircons) rather than shape (rounding) and size. They will, therefore, be quoted more extensively in the two later papers of this series than in the present one. It is of interest to note here that, for instance, Zerndt (1927, p. 373) remarked that, "Die meisten Zirkone in den beiden Quartziten sind *natürlich* stark abgerundet" (italics are the present writer's).

Columbia University, New York. Numerous persons collaborated in obtaining rock samples, or made useful data available to the writer, or contributed by correspondence or in discussions. Although the list of names is too long to give here in full, the writer would like to acknowledge his debt to them all for their cooperation, their interest, and their friendly and constructive criticism.

METHODS

Separation of zircon.—About 500 grams of the rock are crushed to pass through a U. S. Standard 80 mesh (0.22 mm opening) sieve under which is a 100 mesh (0.16 mm opening) sieve. Thus the sample is divided into two portions which are treated separately. Tests indicate that the number of zircons broken by crushing is surprisingly small when the maximum diameter of the grains is less than ½ mm (as it usually is). Particularly if crushing is done mechanically, unusually high proportions of small, broken grains indicate that broken or cracked grains are present in the rock. The powders are placed in 500 cc beakers, water is added and the mixture vigorously agitated, then left to stand for 3 minutes and the water carefully decanted. This is repeated two or three times, after which the washed samples are dried. Next the powders are transferred to 500 cc pear-shaped separatory funnels one-quarter filled with bromoform. More bromoform is added and the mixture thoroughly stirred with a glass rod with paddle-shaped end. During the separation the rod is inserted at intervals of 10-15 minutes to various depths and rotated to agitate in turn the heavy fraction, the material adhering to the sides of the funnel, and the light fraction. The funnel itself is also rotated and slanted at intervals to allow the material adhering to the sides to slide down. The separation is usually complete after 1-1½ hours, when the heavy fraction is filtered off, washed with alcohol, and dried.

For studies of sedimentary heavy residues, slides are prepared from the heavy fractions according to instructions given below, but for specific zircon studies it is more convenient to purify the heavy residues further by magnetic separation and boiling with HCl.

For the magnetic separation the heavy fractions are transferred to a Frantz isodynamic separator. It is best to separate first the strongly magnetic minerals, for which purpose appropriate settings are chosen. The strongly magnetic fraction (mainly magnetite) is set aside, and the less magnetic fraction is run through slowly with different settings to separate all the weakly magnetic minerals. The resulting more magnetic fraction (mainly ilmenite and ferromagnesians) is run through several times with the same settings to augment the nonmagnetic fraction. The latter is then run through once more to obtain a final clean separation. If the sample is a mafic rock (e.g. dolerite), it will be necessary to run both strongly and moderately magnetic fractions through repeatedly to obtain any zircons at all. Patience then becomes a virtue.

To obtain a further concentration of the zircon fraction, the material is finally boiled with conc. HCl for 10-15 minutes to remove apatite and monazite, washed, and dried. If the final residue is very small it consists largely

of zircons, if large there may be present considerable proportions of such minerals as garnet, fluorite, or barite.

At this stage the coarse and fine fractions may be combined or mounted separately, depending on the type of work contemplated. If the amount of final residue cannot be mounted conveniently on one slide, sampling of the residue becomes necessary. The all too frequent practice of tipping part of the residue out of a storage tube onto the slide is to be condemned, as excellent gravitative separations of minerals and of grain sizes are effected by this simple method. Instead, the sampling procedure suggested by Hutton (1950, p. 643) is preferred. It consists of passing the residue through a funnel with a small opening onto a glass surface, thus obtaining a conical heap of residue which is halved with a razor blade. The half removed is passed anew through the funnel and again halved, until a fraction is obtained of suitable size to mount in its entirety on a slide. Mounting is done with stiff Canada balsam, avoiding an excess of balsam, else much of the residue will move toward the sides of the slide on pressing down the cover glass, or will slide down to one side on vertical storage. Care should also be taken in distributing the grains evenly over the slide, avoiding both too high and too low a concentration of grains. In these respects a little practice goes a long way.

Zircon measurements.—Various measurements can be made, and the choice is determined solely by the particular interest and aims pursued in the study. The percentage total heavy residue has been called the *heavy minerals index* (Brammal and Harwood, 1923, p. 40) and is obtained by weighing the original sample and the heavy fraction of the bromoform separation. For most rocks it should correspond roughly with the *color index* of the mode (Shand, 1947, p. 233). The nonmagnetic fraction can similarly be determined and called the *nonmagnetic heavy minerals index*. Relative amounts of the various minerals present can be ascertained by linear traverses with a mechanical stage at regularly spaced intervals covering the entire slide, and counting 300 grains. The amounts may be expressed as volume percentages or after recalculation, as weight percentages of the total residue. The weight percentage of zircon with respect to the total heavy fraction may be called the *zircon index*.

The size of the grains may be determined by measurement with an ocular micrometer of both maximum and minimum diameter of each grain encountered in linear traverses with a mechanical stage at regularly spaced intervals covering the entire slide, care being taken that intervals are wide enough to exclude previously measured grains. Measurements of 200 grains are normally sufficient (Poldervaart and von Backström, 1950, p. 436-437). Broken grains are excluded in these measurements. If the grains are euhedral their length is measured along the *c* axis and their width at right angles thereto. If the grains are rounded the greatest length may or may not coincide with the *c* axis; the width is again measured at right angles to the length. Lengths, widths, and elongation ratios are best analyzed according to the method described by Smithson (1939, p. 349-351) using a moving average of 4 units and moving at intervals of 2 units. Corrections advocated by Smithson need not be applied if all zircons in the microscope field are measured and spaced

intervals cover the entire slide. Final results for lengths and widths should be expressed in mm and frequency percentages, and are conveniently represented graphically. The shapes of these frequency curves and number and positions of maxima are of interest in zircon studies.

Various specific properties of zircons in concentrates may be noted by counting the number of grains which exhibit these properties in a total of 200-300 grains encountered in linear traverses at regularly spaced intervals. For ease of comparison the results may be expressed as percentages. Of especial interest may be for example:

(1) The number of euhedral, versus rounded, versus broken grains.

(2) The number of colorless zircons, versus hyacinths (purple), versus malacons (brown to black).

(3) The number of zircons with a conspicuous crystal face (e.g. the basal pinacoid), versus those without this face.

(4) The number of euhedral zircons with rounded cores, versus those without such cores.

(5) The number of highly elongated (L/B > 4), moderately elongated (L/B 2-4), or slightly elongated (L/B 1-2) grains.

Such counts are more rapid and less tedious than detailed measurements and yet give results of much significance in particular studies. Of especial interest is the proportion of rounded versus sharply euhedral grains. Allen (1944, p. 72) has introduced the term *zircon abrasion index*, being the percentage euhedral crystals (in relation to rounded grains and excluding broken grains). Thus defined the term is not a happy one, and the writer prefers the suggestion of Eckelmann (1954) to call the *zircon rounding index* the percentage of rounded versus euhedral grains (again excluding broken grains). In determining the zircon rounding index especial attention should be given to the terminations of grains; although the grains may show good crystal faces their terminations may be well rounded, and such crystals are rounded, not euhedral.

HARDY QUALITIES OF ZIRCON

Zircon is one of the most resistant of the accessory minerals of sediments, to both chemical attack and abrasion. Table 1 is taken from Smithson (1950, p. 14) and shows relative stabilities of common accessory minerals in sediments. The order of stability was determined both experimentally and empirically.

Table 1 seems to indicate general agreement as to the hardy qualities of zircon in the sedimentary cycle. Yet zircon is not a very hard mineral (H: 7½), and Freise (1931) found that the abrasive resistance of zircon was less than that of such minerals as epidote, garnet, staurolite, rutile, and tourmaline, and of the same order as quartz and apatite. Resistance to chemical attack, the small size of crystals, and the absence of cleavage equally account for the apparent stability of zircon in the processes which make and transport sediments. Another factor is the relative ease with which crystals or broken fragments are modified to more resistant and chemically more inert rounded grains.

TABLE 1
Stability of Accessory Minerals

Mechanical Action	Chemical and Mechanical Action	Chemical Action				
Abrasion tests	Marine shore sands	Subterranean strata		Weathering (?)	Weathering of rocks and soil minerals	
Freise (1931)	Thoulet (1913)	Pettijohn (1941)	Smithson (1941)	Sindowski (1949)	Goldich (1938)	L. and C. Dryden (1946)
		Rutile				
	Zircon	Zircon	Zircon	Zircon		Zircon
	Rutile		Rutile	Rutile		
Tourmaline		Tourmaline	Tourmaline	Tourmaline		Tourmaline
			Apatite			
		Monazite	Monazite			Monazite
Staurolite						
Augite						
Garnet		Garnet	Garnet			
	Biotite	Biotite			Biotite	
Olivine						
Apatite	Apatite	Apatite				
		Staurolite	Staurolite	Staurolite		
Kyanite		Kyanite	Kyanite	Kyanite		Kyanite
	Amphiboles	Hornblende		Amphiboles	Hornblende	Hornblende
			Ferromag-nesian minerals			Staurolite
				Garnet		Garnet
	Pyroxenes	Augite		Augite	Augite	
				Apatite		
	Olivine	Olivine		Olivine	Olivine	
Monazite						

However, this stability is only relative; i.e. zircon generally persists longer than most other minerals. In a finely divided state zircon inevitably loses its stability. In the presence of a solvent, minute particles might dissolve and might again crystallize on larger grains as authigenic growths. Several examples of such zircon outgrowths are reported in the literature (Butterfield, 1936; Smithson, 1937; Tyler et al., 1940; Bond, 1948a; Hutton, 1950), peculiarly enough all from zircons in relatively coarse-grained arenites. It might be expected that in finer-grained sediments (siltstones, shales) zircon outgrowths would be less rare, but so far they have not been observed in such sediments (e.g. Karroo siltstones, Malmesbury semi-pelites, and Pretoria shales, South Africa; Permian siltstones from the Delaware basin, Texas). The problem of zircon outgrowths cannot be regarded as solved until more is known of conditions under which they originated. It may be significant that Hoppe (1951, p. 71-73) has described intergrowths of zircon and xenotime and drawn attention to their close similarity to these zircon outgrowths. Confirmation is needed that the outgrowths are in all instances zircon and not xenotime.

Nonetheless it is clear that eventually zircon is taken into solution. Rankama and Sahama (1950, p. 566) note that, despite the apparent stability of zircon, there is a definite zirconium cycle in nature. Dorothy Carroll (1953, p. 111) observes that zircons in lateritic soil profiles are frequently strongly corroded, and ascribes this to attack by alkaline solutions. Strock (1941, p. 863) attributes the high zirconium content of Saratoga Springs mineral waters to solution of zircon in the country rocks by the carbonated, saline, and lime-rich solutions.

Abundance data for zirconium in sediments are few. The abundance of zircon in sandstones is probably of the same order as that in granite, but subject to large variations, depending also on the amount of reworking of the sediments. Shaw (1954a, p. 1163; 1954b, p. 1179) gives the abundance of zirconium in shales as 200 p.p.m. Yet zircon crops from shales are relatively small, and it is suspected that a considerable proportion of zirconium in shales is not present as zircon. Cherts contain no zirconium (Maxwell, 1953). The abundance of zirconium in oceanic red clay is given by Hevesy and Würstlin (1934, p. 309; Atlantic samples) as 140 p.p.m., and by Young (1954) as 230 p.p.m. The chocolate brown clays of the South Pacific, high in fine-grained pyroclastics, average about 220 p.p.m., and the light buff North Pacific clays about 150 p.p.m. zirconium (Gustaf Arrhenius, personal communication, Nov. 19, 1954). Yet zircon is rarely observed and the zirconium content of the clays varies with iron, indicating sorption of complex zirconium anions on hydrated ferric oxides (Revelle et al., 1955). Thus zirconium in oceanic clays, which may be regarded as the end products of the sedimentary cycle, is not present as zircon.

SIZE AND SHAPE OF SEDIMENTARY ZIRCONS

The implications of table 1 are clear: (1) Away from source, with repeated reworking, or traced back in geologic time, both the total amount of accessory minerals and the number of mineral species ("richness" of mineral assemblage) are likely to diminish (Pettijohn, 1941). (2) If a sediment is traced away from its source or is reworked repeatedly, the proportion of zircon relative to other accessory minerals is likely to increase gradually. Various uses have been made of these observations; it suffices here to refer to Smithson's studies (1941, 1942) of Mesozoic arenites of Yorkshire.

Assuming an original source in which the zircons are prismatic crystals with sharply pointed pyramidal terminations, it would appear likely that the sharp points would be rounded off relatively rapidly during sedimentary transport. Further away from the source, and more slowly, the grains would tend to become more rounded in shape, by rounding of both original prismatic crystals and angular chips and fragments resulting from breakage (fig. 1). Yet further away from source there would probably be increasing amounts of small, roughly equidimensional, angular fragments, in addition to well-rounded grains. Finally there would be a predominance of minute, angular fragments over rounded grains, and much fine zircon flour which normally would not be recovered in heavy mineral separations. The same effects would be produced by repeated reworking without much lateral transport. The effect

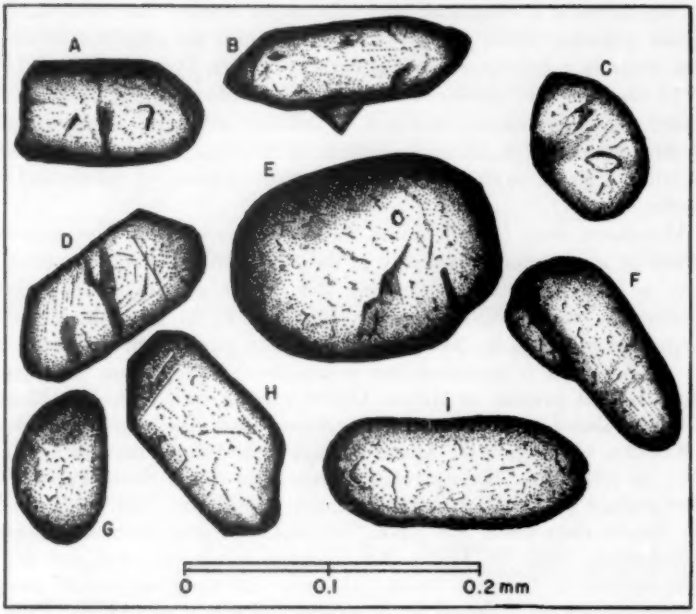


Fig. 1. Habit of zircons in sandstones.
A. Fractured grain with rounded end.
B. Partly rounded grain with sharply euhedral outgrowth.
C., G. Rounded grains in which terminal faces can still be faintly seen.
D. Partly rounded, partly euhedral, zoned grain.
E. Well-rounded grain.
F., I. Well-rounded but elongated grains.
H. Fractured grain, partly euhedral and partly rounded.

of grain-size of zircons should be considered, as well as distance from source or amount of reworking prior to final deposition. Larger grains would tend to round more rapidly than smaller crystals. The latter may be carried further or reworked to a greater extent without losing their sharply euhedral original shapes.

These predictions are generally realized in studies of zircons in various sediments. On the whole, sorting of sediments is reflected also in sorting of their zircons. Well-sorted sediments yield zircon length- or elongation-frequency curves with one narrowly defined maximum, whereas ill-sorted sediments may yield zircon curves with broad peaks or several maxima, depending also on zircon size distribution in the source rocks. The inequidimensional character of zircon in most source rocks generally results in zircons separated from a particular size grade of a sediment being longer than conforms with the average diameter of quartz of that size grade. The size of zircons which passes through a sieve is determined by the widths of the grains rather than their lengths.

In arkoses there are usually many zircons with sharp as well as rounded terminations, but in most sandstones angular zircon fragments and sharply terminated crystals are subordinate to grains with well-rounded terminations. In both arkoses and sandstones the average longest diameter of zircons is generally 0.15-0.25 mm. In most siltstones there is an appreciable proportion of angular zircon fragments in addition to rounded grains. Generally the average longest diameter of zircons is 0.05-0.15 mm. In most shales the proportion of zircons recovered is relatively small, rounded grains are subordinate to angular fragmental grains, while sharply terminated crystals are rare or absent. The average longest diameter of zircons is usually 0.02-0.07 mm.

It is to be noted that in the series arkose-sandstone-siltstone-shale, the largest proportions of sharply terminated zircon crystals are to be found in arkoses and siltstones, the euhedral grains being large (length > 0.12 mm) in the former and small (length < 0.10 mm) in the latter.

Rounding and breakage of primary crystals results in a rapid decrease in average elongation ratio of zircons in sediments when traced away from their source, or when repeatedly reworked. In most igneous rocks the average elongation ratio of zircons is less than 3.0. Accordingly, the average elongation ratio of zircons in most sediments is less than 2.0, and approaches 1.0 in fine-grained sediments. However, some igneous rocks may contain small, slender zircons with elongation ratios much in excess of 3.0. Their significance will be discussed later. Sediments derived from such rocks commonly contain zircons with rounded terminations, but with elongation ratios greater than 2.0, even when transported over considerable distances or reworked repeatedly. Apparently the small size of the zircons prevents much breakage in spite of their slender form.

The above observations allow for certain general conclusions which are at least statistically true, although exceptions may be found:

(1) Zircons of sediments are predominantly grains with rounded terminations, or angular fragments, but sharply pointed, euhedral crystals are generally subordinate.

(2) The average elongation ratio of such zircons is generally less than 2.0.

(3) The average size of zircons in arenites decreases toward that of lutites, while at the same time the proportion of rounded grains decreases and that of angular fragments increases.

Studies of zircon size and shape distribution are not particularly useful in paleogeographical investigations of sediments. Generally it is found that, e.g. the same sandstone sequence, even when traced through a considerable distance, contains zircons of the same or similar size and shape distributions. For such investigations the relative proportions of the heavy nonopaque minerals, including zircon, and the size distribution of other common accessory minerals (e.g. garnet, staurolite, kyanite, sillimanite, andalusite) may yield more satisfactory results. However, data on zircons in sediments form the basis for zircon studies of metamorphosed or granitized rocks. Hence there is a real need for information of this type.

TABLE 2

Characteristic Nonopaque Heavy Minerals in Kalahari Sand
Surface Samples from Ukwe Pan to Kanye

Index	L 196	L 197	L 198	P 292	P 285	P 291	L 200	P 286	P 283	L 203	P 287	P 284	P 290	L 205	P 282	L 206	L 207	L 208	P 289
Distance from Ukwe Pan (miles)	32	36	46	113	130	133	137	147	176	194	195	201	208	218	231	246	276	288	303
Zircon	23	25	36	40	41	35	36	43	42	41	52	50	39	43	47	44	46	48	48
Tourmaline	22	26	27	29	29	33	30	25	28	30	23	21	32	32	26	33	33	30	29
Staurolite	41	36	22	20	22	19	20	18	20	18	15	16	19	15	17	16	14	15	15
Kyanite	6	6	8	5	3	4	4	4	3	4	3	5	4	4	3	3	2	2	2
Rutile	8	7	7	6	5	9	10	10	7	7	7	8	6	6	7	4	5	5	6

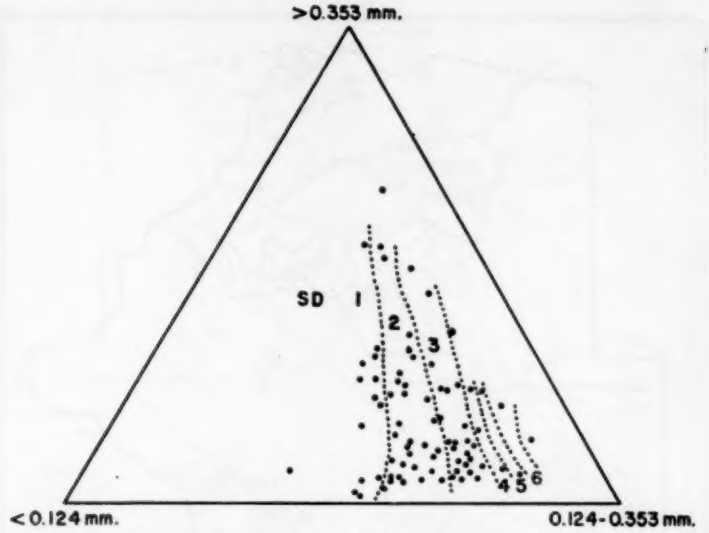


Fig. 2. Size distribution of quartz grains in Kalahari sands, Bechuanaland Protectorate.

MALACONS IN SEDIMENTS

Little is known of the role of malacons in sediments. Gross observations on heavy residues of arenites indicate that brown or black zircons are relatively rare; hence it may be concluded that the stability of malacon is lower than that of clear or colorless zircon, and that the former crystals break more easily and are also more easily attacked by solutions. The Precambrian Mahalapye granite in the Bechuanaland Protectorate (Poldervaart and Green, 1954) contains a high proportion (about 75 percent) of brown and black zircons. In places the granite is overlain by highly feldspathic grits, arkoses, and sandstones which so closely resemble the granite that their local derivation can hardly be in doubt. Heavy residues of the sediments confirm this; the proportion of euhedral crystals with sharp terminations is relatively high (about 20 percent) and they are identical in shape and size to the colorless zircons of the granite (rather small, squat crystals with a small basal pinacoid). However, only some 25 percent of the grains are brown, indicating relatively rapid dissolution of malacon in the formation of the sediments.

Siltstones are in this respect similar to sandstones, i.e. they contain relatively few malacons. On the other hand, shales often contain a considerable proportion of gray, brown, or black zircons. Probably original malacons fracture easily to minute grains which are carried further and thus concentrated in sediments of finest grain-size. This may be a contributing factor, but it cannot be the only reason for the paucity of malacons in sandstones and siltstones and their relative concentration in shales, since they are probably also more easily attacked by solutions than clear zircons. The writer suggests that water under favorable conditions may promote the production of malacon.

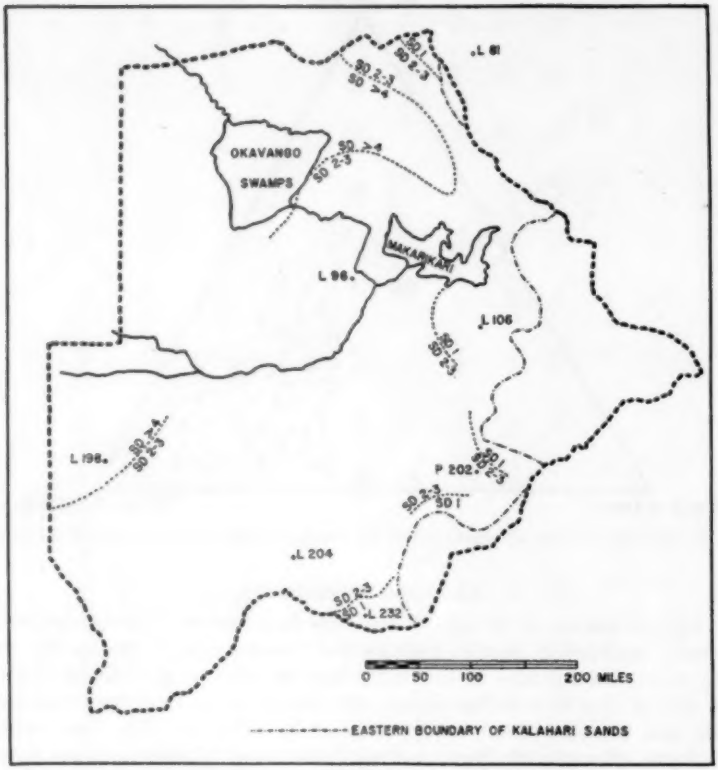


Fig. 3. Geographic distribution of SD (sand-dust) ratios in Kalahari sands, Bechuanaland Protectorate.

Thus he interprets the apparent concentration of brown and black zircons in shales as due in part to their formation during and after deposition, facilitated by both the solutions contained by shales and the extremely small size of the majority of zircons present. This will be discussed further in the second paper of this series.

EXAMPLES

Kalahari sands, Bechuanaland Protectorate[2].—The present work was done on about 100 samples with a wide geographic spread. Considering the large area involved the number of samples is woefully small, and this study can only be regarded as a reconnaissance.

[2] Data given here are derived in part from an unpublished report by the writer while at the Geological Survey of the Protectorate. Permission of the Director is acknowledged for publication of these results.

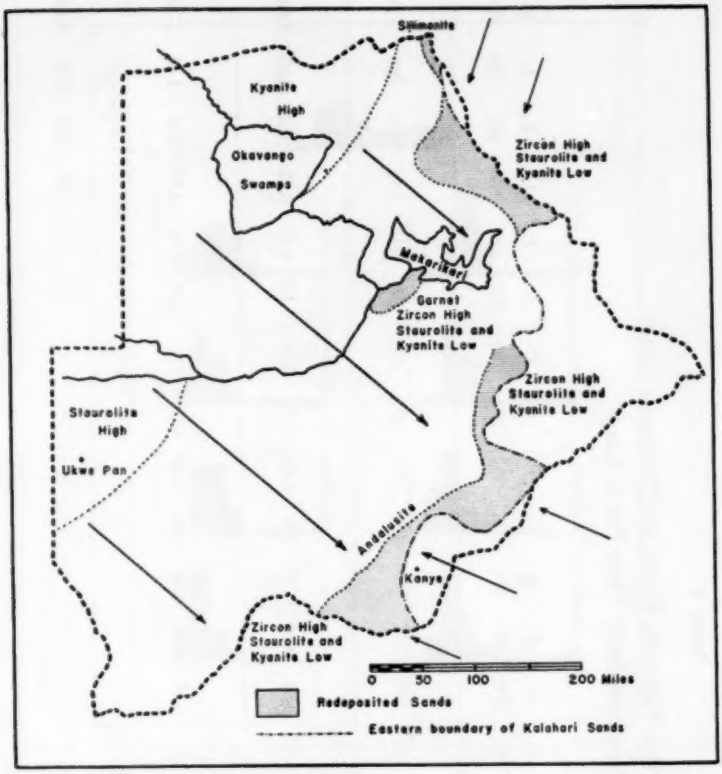


Fig. 4. Geographic distribution of nonopaque heavy minerals in Kalahari sands, Bechuanaland Protectorate.

Sieving results indicate that the sands are uniformly well sorted. Figure 2 shows percentages of the quartz fractions $>$ 0.353, 0.124-0.353, and $<$ 0.124 mm diam. for 77 samples plotted on a triangular diagram. The lines drawn separate fields for which $\text{SD} = \dfrac{\text{weight percent 0.124-0.353 mm}}{\text{weight percent} < \text{0.124 mm}}$ equals 1, 2, 3, 4, etc. Figure 3 is a sketch map of the Protectorate on which the distribution of SD (sand-dust) ratios is indicated geographically. The proportion of dust increases in a general southeasterly direction.

Typical nonopaque heavy minerals of Kalahari sands are zircon, tourmaline, staurolite, kyanite, and rutile. Minerals such as garnet, sillimanite, andalusite, epidote, augite, and hornblende may be present locally. Figure 4 indicates the geographic distribution of differences in proportions of these minerals. Sands with high staurolite and kyanite proportions are found in the western and northwestern parts of the Protectorate and seem to be differentiated from one another. Proportions of these two minerals decrease in a

TABLE 3

Diameters of Largest Staurolite, Zircon, and Andalusite Grains
in Kalahari Sand Series Ukwe Pan to Kanye

Index	L 196	L 197	L 198	P 292	P 285	P 291	L 200	P 286	P 283	L 203	P 287	P 284	P 290	L 205	P 282	L 206	L 207	L 208	P 289
Distance from Ukwe Pan (miles)	32	36	46	113	130	133	137	147	176	194	195	201	208	218	231	246	276	288	303
Diam. largest staurolite (mm)	0.66	0.48	0.60	0.41	0.52	0.42	0.38	0.64	0.50	0.51	0.46	0.32	0.36	0.42	0.48	0.45	0.51	0.36	0.68
Diam. largest zircon (mm)	0.33	0.37	0.31	0.30	0.34	0.30	0.33	0.28	0.36	0.40	0.46	0.26	0.30	0.39	0.30	0.39	0.39	0.48	0.32
Diam. largest andalusite (mm)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.29	0.52	0.56	0.44

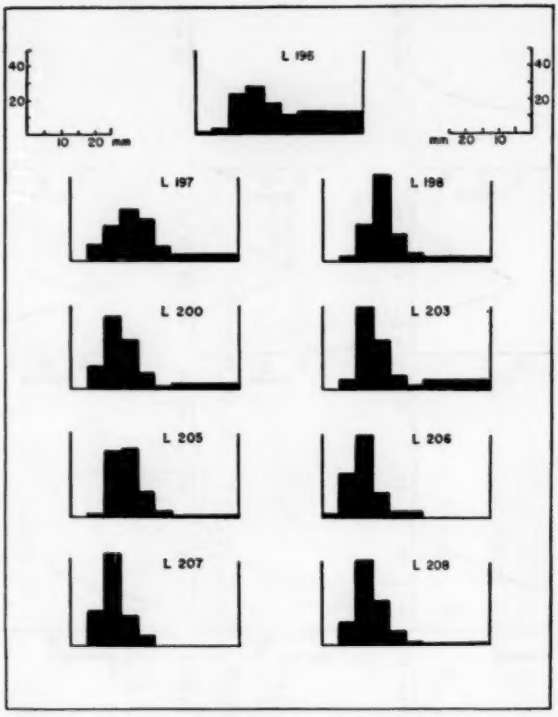


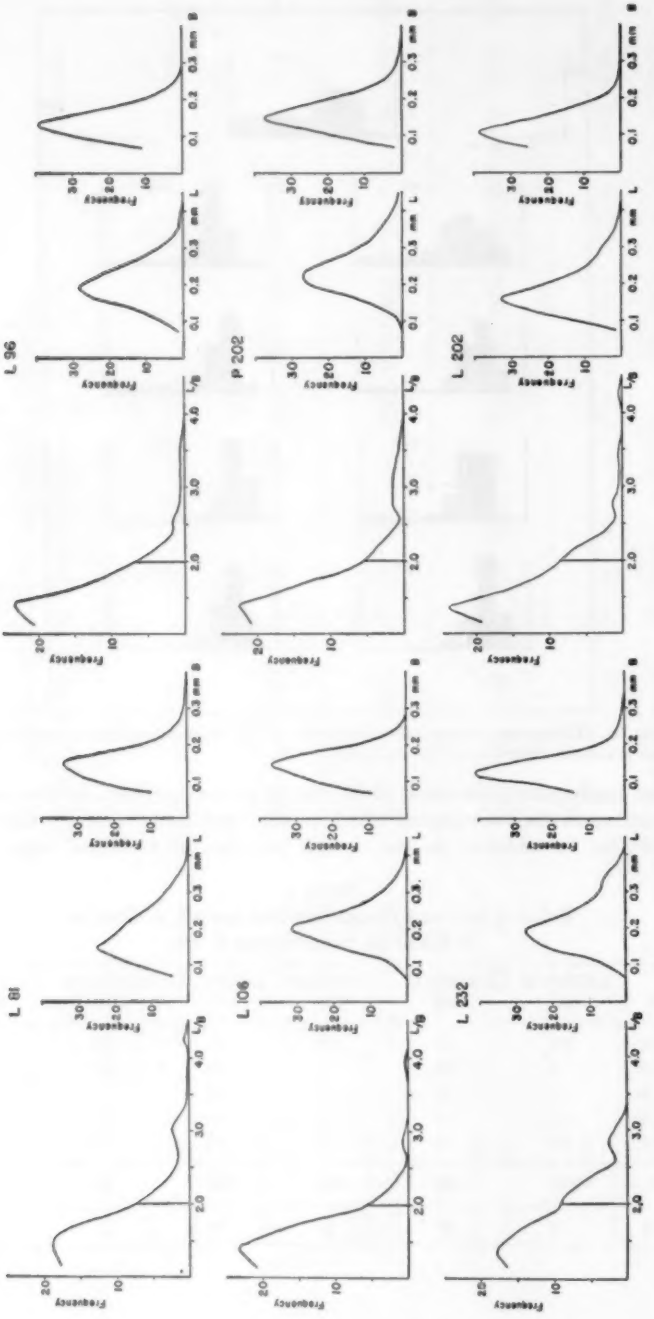
Fig. 5. Histograms of maximum diameter of 100 staurolite grains in series of Kalahari surface sands from Ukwe Pan to Kanye.

general southeasterly direction while that of zircon increases. In the southeast and east sands are encountered which contain andalusite, epidote, augite, and hornblende, in addition to the typical minerals of Kalahari sands. Since

TABLE 4

Relation between Elongation and Length of Zircons in Kalahari Sand Sample L 196

L/B	L 0.05-0.10 mm	L 0.10-0.15 mm	L 0.15-0.20 mm	L 0.20-0.25 mm	L 0.25-0.30 mm	L >0.30 mm
1.0-2.0	97	80	92	71	27	10
2.0-3.0	3	18	7	24	17	3
3.0-4.0	—	2	1	4	5	1
4.0-5.0	—	—	—	—	1	1
5.0-6.0	—	—	—	1	—	—
total	100	100	100	100	50	15
> 2.0	3	20	8	29	23	5


L 96
P 202
L 202
L 81
L 106
L 232
Frequency
mm L
mm B
$L_{/B}$

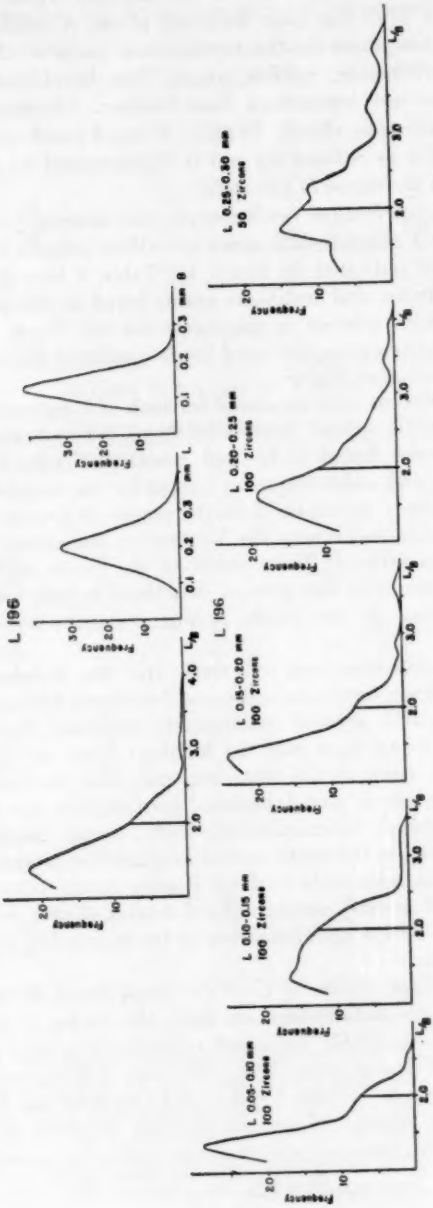


Fig. 6. Zircon size-frequency curves of 7 samples of Kalahari sands (for locations see figure 3).

andalusite increases eastward these sands are regarded as redeposited and blown back into the Kalahari basin from the Bushveld region (a likely source for the andalusite) after the main Kalahari phase. A similar belt of redeposited sands is recognized in the northeastern parts of the Protectorate, characterized by sillimanite, epidote, augite, and hornblende. These sands are thought to have been blown back from Southern Rhodesia in a southerly or southwesterly direction (Bond, 1948b). A small patch south of Makarikari is also regarded as redeposited and is characterized by garnet, epidote, and hornblende. Its derivation is uncertain.

Table 2 shows percentages (exclusive of other minerals) of typical heavy residue minerals in a characteristic series of surface samples from Ukwe Pan to Kanye (locations indicated on figure 4). Table 3 lists diameters of the largest staurolite, zircon, and andalusite grains found in this series. Evidently there is no systematic variation in maximum size (cf. Bond, 1948b). Histograms of 100 staurolite grains measured for 9 samples of the series also show lack of systematic variation (fig. 5).

Two hundred zircons were measured for each of 7 representative samples with a wide geographic spread. Sample locations are indicated on figure 3. All zircon grains were found to be well rounded. Figure 6 shows zircon elongation-, length-, and width-frequency curves for the samples.[3] Also shown are elongation-frequency curves for 5 length ranges of zircons of one sample (L 196). Further data concerning the relation of elongation and length of zircons are given in table 4. These illustrate the points made in previous sections of this paper. It is also evident that there is little variation in size distribution of zircons in the sands, despite transport over considerable distances.

Preliminary conclusions from this study are: The Kalahari sands were originally derived from a source, or sources in Southwest Africa or Portuguese Angola, and blown in a general southeasterly direction. Subsequently the sands were in part blown back into the Kalahari basin, resulting in fringe areas of redeposited sands in the southeast, east, and northeast. It is noteworthy that evidence for a post-Acheulean, pre-Levallois age for the sands (E. J. Wayland, personal communication, 1951) comes chiefly from these fringe areas and leaves in doubt the age of original distribution of the Kalahari sands. Much work remains to be done. It seems to the writer that detailed archeological and sedimentary petrographical studies of cave deposits (King, 1951), coupled with C^{14} age determinations as far as possible, should be most profitable in this research.

Arenites of the Cape system in Cape Province, South Africa.—For general information on this sedimentary sequence, the reader is referred to du Toit (1939). De Villiers (1942) published a detailed structural study of part of the Cape Folded Belt and also (1945) discussed more general aspects of the Cape orogeny. Coetzee (1942a, 1942b), and Conradie and Rabie (1945) studied heavy residue minerals of samples of Table Mountain sandstone, and

[3] Using Smithson's method, frequency percentages are obtained at regular intervals, e.g. for L/B at 1.15, 1.35, 1.55, etc. No specific points are shown on the curves which were faithfully drawn through all the points obtained.

TABLE 5

Relation between Elongation and Length of Zircons in Table Mountain Sandstone Sample from Schoenmakers Kop

L/B	L 0.05-0.10 mm	L 0.10-0.15 mm	L 0.15-0.20 mm	L 0.20-0.25 mm	L >0.25 mm
1.0-2.0	99	167	44	10	—
2.0-3.0	1	33	53	52	2
3.0-4.0	—	—	2	33	2
4.0-5.0	—	—	1	5	1
5.0-6.0	—	—	—	—	1
total	100	200	100	100	6
> 2.0	1	33	56	90	6

TABLE 6

Characteristic Nonopaque Heavy Minerals in Cape Sediments at Wuppertal

		Zircon	Rutile	Brookite	Tourmaline	Monazite
Witteberg series (base)		55	16	20	9	–
Bokkeveld series						
S_3	top	64	19	9	4	4
	middle	56	25	12	3	4
	bottom	54	24	16	2	4
S_2	top	59	22	9	7	3
	middle	56	21	16	4	3
	bottom	66	17	5	7	5
S_2	top	70	17	3	9	1
	middle	69	17	6	4	4
	bottom	66	18	4	8	4
S_2	top	69	24	1	5	1
	middle	70	23	1	6	+
	bottom	73	20	2	4	1
S_1	top	72	18	4	6	+
	middle	80	14	+	6	+
	bottom	81	7	+	11	1
Table Mountain series (top)		54	30	–	15	1

Swart (1950) investigated Cape sediments around Wuppertal. Present data are largely derived from the last three papers with the addition of results for two samples of Table Mountain sandstone obtained by the writer.

Figure 7 shows the geographic distribution of the samples discussed here. Figure 8 gives zircon elongation-frequency curves for Table Mountain Sandstone samples from two localities and different horizons, measured by Coetzee

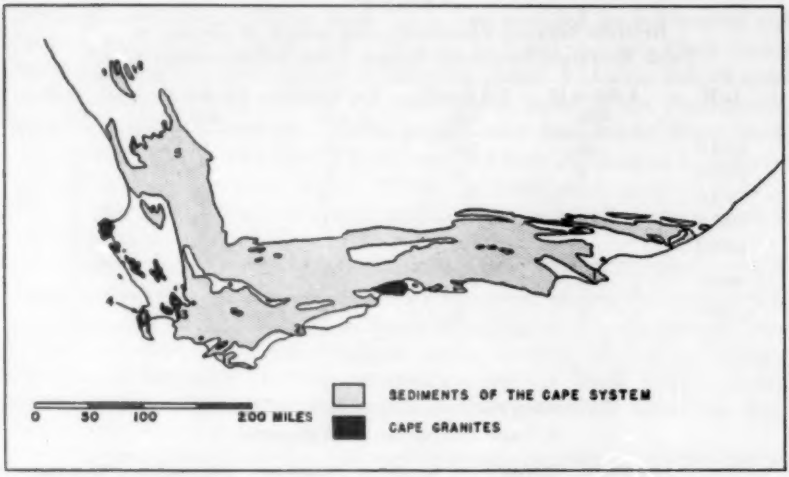


Fig. 7. Geographic distribution of samples of Cape sediments examined.
1. Table Mountain sandstone, Schoenmakers Kop, near Port Elizabeth.
2. Table Mountain sandstone, Mosselbay.
3. Table Mountain sandstone, base of series, Botmanskop, near Stellenbosch.
4. Table Mountain sandstone, just above lower shale band, Cape Town.
5. Cape sediments, Wuppertal district.

(1942b) and Conradie and Rabie (1945), and complete zircon size-frequency curves for two other samples measured by the writer. Also shown are elongation-frequency curves for four length ranges of zircons of one sample (Schoenmakers Kop). Further data are given in table 5. Figure 9 gives zircon elongation-frequency curves for Cape sediments of the Wuppertal district measured by Swart (1950). Table 6 lists percentages of nonopaque heavy minerals in the Wuppertal samples given by Swart (1950).

Conclusions reached in preceding sections are well illustrated by these data. This is not the place for a detailed discussion of conditions of deposition of the Cape sediments, nor are there probably sufficient data for such a discussion, nor is the writer the best qualified to do so. However, one point deserves mention here. The so-called Cape granites (Scholtz, 1946; Walker and Mathias, 1947; Potgieter, 1950) are characterized by highly elongated "needle" zircons often with unusually steep pyramidal terminations, probably (331).[4] No other granites in southern Africa examined by the writer possess zircons of this habit and with such steep pyramid faces. Zircons of the Table Mountain samples usually have rounded terminations, but many are long and bar-shaped. There is a small proportion of grains in which pyramidal faces can still be recognized, although points and edges are usually rounded off. These zircons show the same steep pyramid faces and leave little doubt that the grains are in large part derived from the Cape granites. Swart (1950, p. 441)

[4] See further the second paper of this series.

remarks that in the arenites of Bokkeveld and Witteberg age from Wuppertal, zircons with steep pyramidal faces are not frequent. This may indicate a different principal source for these sediments but the similarity of elongation-frequency curves for the Witteberg and Table Mountain sandstones should be noted. More systematic work of this nature is needed. The Table Mountain sandstone seems to be an accumulation of beach sands, reworked repeatedly but not transported far, and derived in large part from the Cape granites.

Permian arenites of New Mexico, Oklahoma, and Texas.—Data given here were obtained by Mr. J. P. D. Hull, Jr. during his research work on these sediments at this University. The writer is indebted to him for making these data available for this paper.

King (1948, p. 83-84) has summarized information concerning the Guadalupian series of the Delaware Basin of western Texas. Some 3000 feet of well-sorted sand and silt were here deposited in deep water of the fore-reef environment of the basin. Arenites are common also throughout the larger Permian basin of the southwest-central United States. Lang (1937, p. 888-890) and Newell et al. (1953, p. 185-186) have suggested that the sands were derived from distant sources of older arenites.

Locations of the 6 samples discussed here are given in figure 10. Stratigraphers disagree on correlation of some of the Permian units, but the samples represent approximately the base of the middle Guadalupian series, or the base of the Cherry Canyon formation (Adams et al., 1939, p. 1676). Typical nonopaque heavy minerals are zircon, tourmaline, apatite, rutile, and garnet, with minor amounts of staurolite, anatase, and sphene.

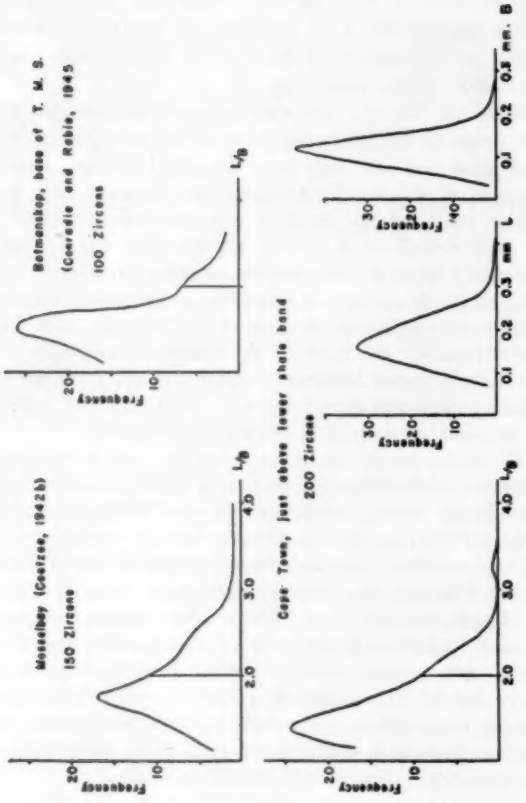
Figure 11 shows zircon elongation-, length-, and width-frequency curves for the 6 samples. Several samples contain a small proportion of highly elongated, needle-shaped zircons with well-rounded terminations. However, the maximum elongation-frequency in all cases is well below 2.0.

Table 7 shows data obtained for a sample of the Glorieta sandstone member of the Permian San Andres formation, from Glorieta Mesa, near Rowe, San Miguel County, New Mexico. The sample consists for 72 percent of fine sand (0.250-0.125 mm). It was graded into 5 portions by sieving and elutriation, and zircons were separated from each portion. Grains are divided into 3 classes; (1) essentially euhedral crystals, including those with slightly rounded terminations, (2) well-rounded grains, and (3) fragmental grains, including those with slight rounding of sharp edges and points. Results are given in percentages on counts of 200-400 zircons.

TABLE 7

Distribution of Zircons in Glorieta Sandstone Sample

Grade (mm)	0.177-0.125 fine sand	0.125-0.088 very fine sand	0.088-0.062 very fine sand	0.062-0.044 silt	0.044-0.031 silt
Class 1	0	0	0	2	5
Class 2	87	78	66	47	20
Class 3	13	22	34	51	75


Belmontop, base of T. M. S.
(Cowradie and Robie, 1945
100 Zircons
Frequency
L/B
Mosselbay (Coetzee, 1942b)
150 Zircons
Cape Town, just above lower shale band
200 Zircons
0.1 0.2 0.3 mm. L
0.1 0.2 0.3 mm. B
2.0 3.0 4.0

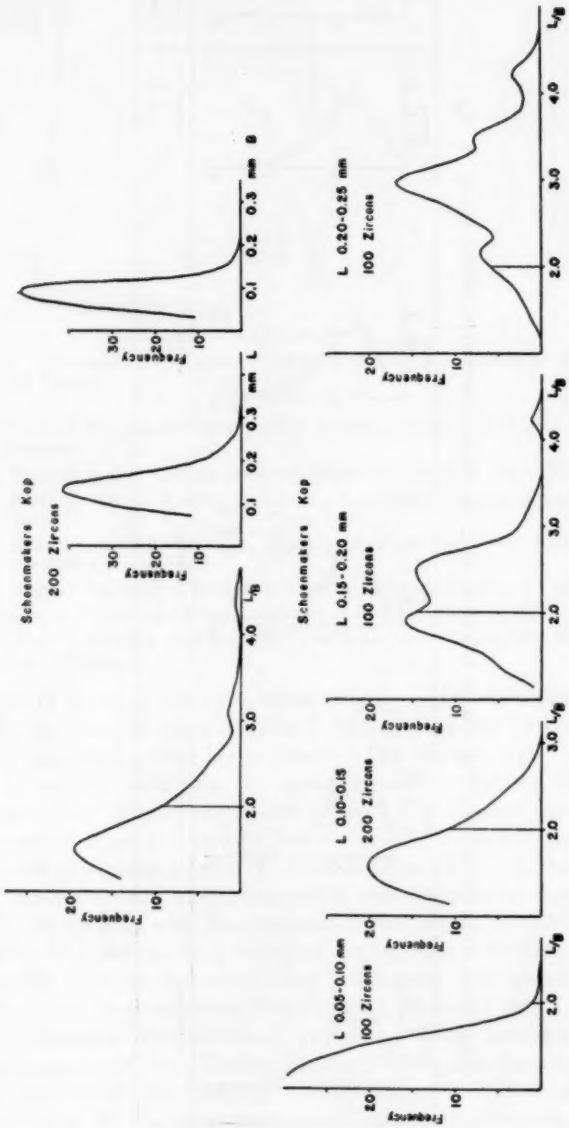


Fig. 8. Zircon size-frequency curves of 4 samples of Table Mountain sandstone (for locations see figure 7).

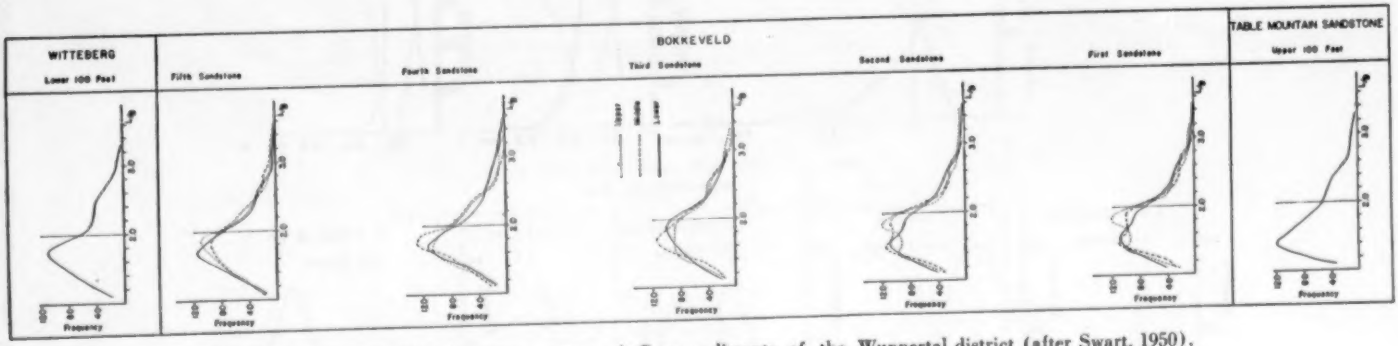


Fig. 9. Zircon elongation-frequency curves of Cape sediments of the Wuppertal district (after Swart, 1950).

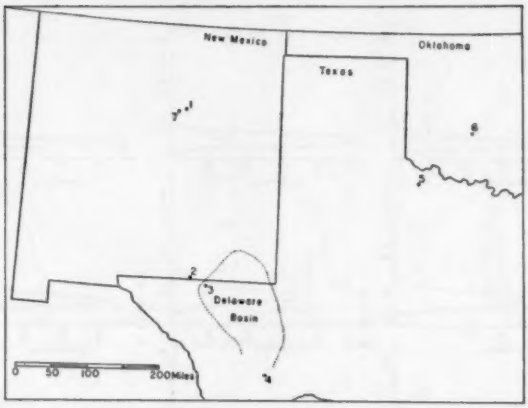


Fig. 10. Geographic distribution of samples of Permian arenites in the southwest-central United States.

1. Base of Glorieta sandstone, south of Romeroville, San Miguel County, New Mexico.
2. Base of Cherry Canyon, Brokeoff Mountains, Otero County, New Mexico.
3. Base of Cherry Canyon formation, Guadalupe Canyon, Culberson County, Texas.
4. Just above third limestone member of Word formation, Glass Mountains, Brewster County, Texas.
5. Base of San Angelo sandstone, south of Quanah, Hardeman County, Texas.
6. Base of Duncan sandstone, southwest of Fletcher, Comanche County, Oklahoma.
7. Base of Glorieta sandstone, Glorieta Mesa, near Rowe, San Miguel County, New Mexico.

Figure 12 shows zircon elongation-, length-, and width-frequency curves for the 4 largest size portions of table 7. The smallest size portion contained insufficient unbroken grains for evaluation. The "sieve ranges" are also indicated. It may be noted that (1) sieving results in sorting of zircons by width rather than length, (2) "sieve ranges" may depart markedly from width ranges of zircons, especially for the smaller sieve openings, and (3) the maximum elongation frequency increases from 1.2 to 1.6, the curves also widening toward greater elongation ratios, with decreasing size of zircons. The last is in keeping with the observation that small, slender zircons will remain unbroken, despite long transport or repeated reworking.

Examples from the literature.—Few publications give specific frequency curves for zircon measurements. Rao (1953a) published data for the lower Cuddapah quartzites (Precambrian) and also (1953b) for the upper Gondwana sandstones, both from Madras. Henzen (1950) gave data comparing the Rooiberg arenites of the Rooiberg and Stavoren-Vlakfontein areas in the Transvaal, South Africa. Apart from contributing to local geologic problems, these studies fully confirm conclusions reached in preceding sections of this paper.

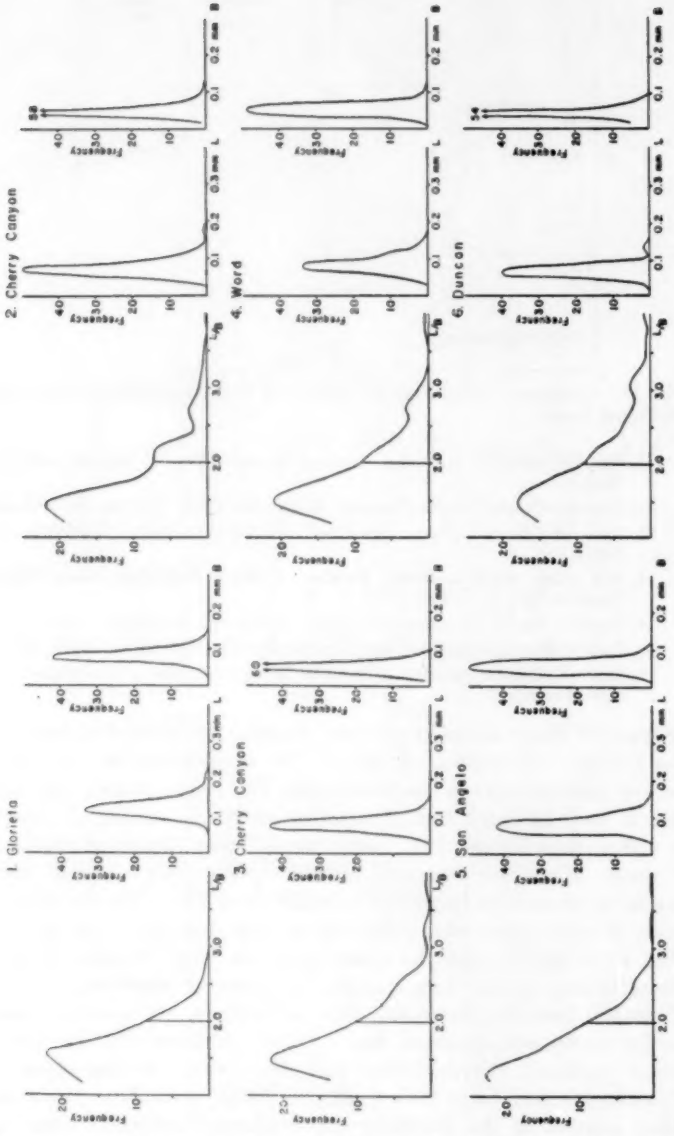


Fig. 11. Zircon size-frequency curves of 6 samples of Permian arenites (for locations see figure 10).

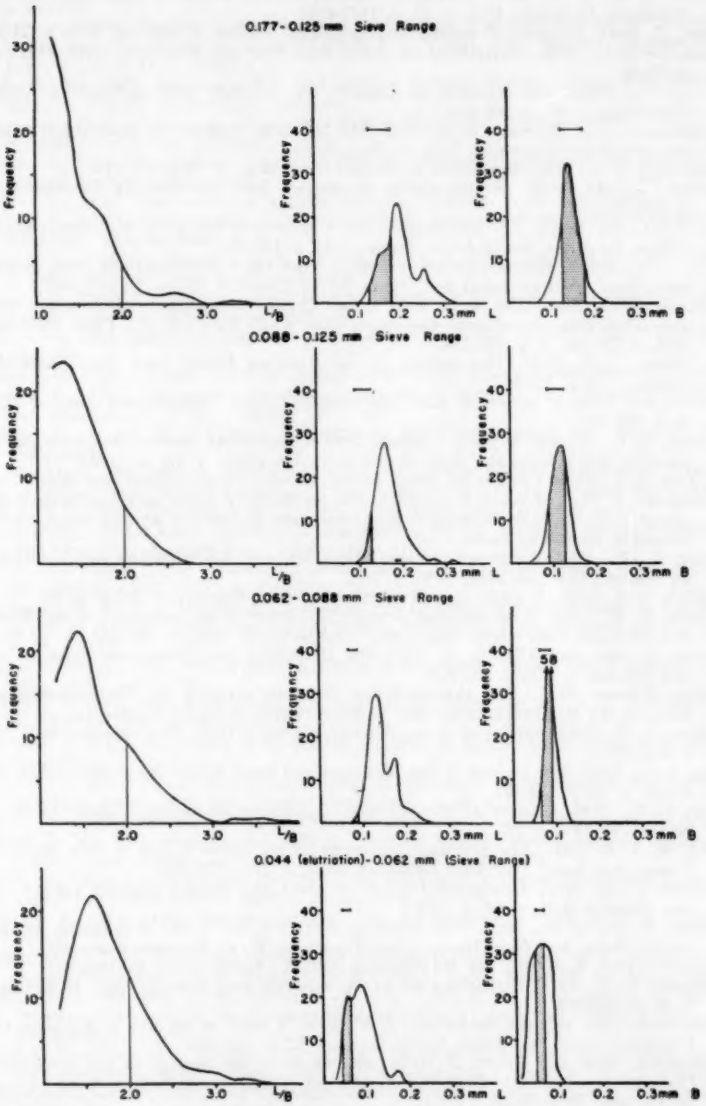


Fig. 12. Zircon size-frequency curves for 4 size fractions of a sample of Glorieta sandstone, Glorieta Mesa, near Rowe, San Miguel County, New Mexico.

References

Adams, J. E., et al., 1939, Standard Permian section of North America: Am. Assoc. Petroleum Geologists Bull., v. 23, p. 1673-1681.

Allen, P., 1944, Statistics in sedimentary petrology: Nature, v. 153, no. 3872, p. 71-74.

Bond, Geoffrey, 1948a, Outgrowths on zircon from Southern Rhodesia: Geol. Mag., v. 85, p. 35-40.

———, 1948b, The direction of origin of the Kalahari sand of Southern Rhodesia: Geol. Mag., v. 85, p. 305-313.

Brammal, A., and Harwood, H. F., 1923, The Dartmoor granite; its mineralogy, structure, and petrology: Mineralog. Mag., v. 20, p. 39-53.

Butterfield, J. A., 1936, Outgrowths on zircon: Geol. Mag., v. 73, p. 511-516.

Carroll, Dorothy, 1953, Weatherability of zircon: Jour. Sedimentary Petrology, v. 23, p. 106-116.

Coetzee, C. B., 1942a, The petrology of the Goodhouse-Pella area, Namaqualand, South Africa: Geol. Soc. South Africa Trans., v. 44, p. 167-206.

———, 1942b, Metamorphosed sediments from the Goodhouse-Pella area, Namaqualand, South Africa: Royal Soc. South Africa Trans., v. 29, pt. 2, p. 91-112.

Conradie, W. F., and Rabie, L. P., 1945, A petrographic investigation of the heavy residues associated with the alluvial cassiterite from Kuils River, C. P.: Univ. Stellenbosch Ann., v. 22, sec. A, p. 105-134.

de Villiers, J. E., 1942, The geology of the Baviaans Kloof: Geol. Soc. South Africa Trans., v. 44, p. 151-161.

———, 1945, A review of the Cape orogeny: Univ. Stellenbosch Ann., v. 22, sec. A, p. 183-208.

Dryden, A. L., Jr., and Dryden, Clarissa, 1946, Comparative rates of weathering of some common heavy minerals: Jour. Sedimentary Petrology, v. 16, p. 91-96.

du Toit, A. L., 1939, Geology of South Africa, 2d ed.: London, Oliver and Boyd.

Eckelmann, F. D., and Kulp, J. L., 1954, The sedimentary origin and stratigraphic equivalence of the so-called Cranberry and Henderson granites in western North Carolina: Columbia University thesis.

Freise, F. W., 1931, Untersuchung von Mineralen auf Abnutzbarkeit bei Verfrachtung im Wasser: Min. pet. Mitt., v. 41, p. 1-7.

Goldich, S. S., 1938, A study in rock weathering: Jour. Geology, v. 46, p. 17-58.

Henzen, M. R., 1950, A comparative petrographic study of the sediments of the Rooiberg and Stavoren-Vlakfontein areas: Univ. Stellenbosch Ann., v. 26, sec. A, p. 307-322.

Hevesy, G. von, and Würstlin, J., 1934, Die Häufigkeit des Zirconiums: Zeitschr. anorg. allg. Chemie, v. 216, p. 305-311.

Hoppe, Günter, 1951, Die akzessorischen Schwermineralien in Eruptivgesteinen am Beispiel des Rambergranites und anderer Harzer Gesteine: Geologica, no. 9.

Hutton, C. O., 1950, Studies of heavy detrital minerals: Geol. Soc. America Bull., v. 61, p. 635-716.

King, L. C., 1951, The geology of the Makapan and other caves: Royal Soc. South Africa Trans., v. 33, p. 121-151.

King, P. B., 1948, Geology of the southern Guadalupe Mountains, Texas: U. S. Geol. Survey Prof. Paper 215.

Lang, W. T. B., 1937, The Permian formations of the Pecos Valley of New Mexico and Texas: Am. Assoc. Petroleum Geologists Bull., v. 21, p. 833-898.

Maxwell, J. A., 1953, Geochemical study of chert and related deposits (abst.): Geol. Soc. America Bull., v. 64, p. 1452.

Newell, N. D., et al., 1953, The Permian reef complex of the Guadalupe mountains region, Texas and New Mexico: San Francisco, W. H. Freeman Company.

Niggli, P., 1924, Lehrbuch der Mineralogie, Band 1: Berlin, Gebr. Borntraeger.

Pettijohn, F. J., 1941, Persistence of heavy minerals and geologic age: Jour. Geology, v. 49, p. 610-625.

Poldervaart, Arie, and von Backström, J. W., 1950, A study of an area at Kakamas (Cape Province): Geol. Soc. South Africa Trans., v. 52, p. 433-495.

Poldervaart, Arie, and Green, D., 1954, An outline of the geology of the Bechuanaland Protectorate: Internat. Geol. Cong., Algiers, 1952, Assoc. Service Géol. Africains, 1e. Pt., fasc. 20, p. 53-66.

Potgieter, C. T., 1950, The structure and petrology of the George granite plutons and the invaded pre-Cape sedimentary rocks: Univ. Stellenbosch Ann., v. 26, sec. A, p. 323-412.

Rankama, K., and Sahama, T. G., 1950, Geochemistry: Chicago, Univ. Chicago Press.

Rao, C. G., 1953a, Statistical studies in the heavy mineral assemblages of the Gulcheru and the Pulivendla quartzites of the lower Cuddapah formations (Precambrian)

near Rayalacheruvu, Anantapur district, Madras: Mysore Univ. Jour., sec. B, v. 13, p. 247-258.
————, 1953b, Statistical studies in the heavy mineral assemblages of the Sriperumbudur and the Satyavedu stages (upper Gondwana) near Madras: Mysore Univ. Jour., sec. B, v. 13, p. 259-269.
Read, H. H., 1939, Metamorphism and igneous action: British Assoc. Adv. Science, sec. C, p. 223-251 (presidential address).
————, 1943, Meditations on granite. Part I: Geologists' Assoc. London Proc., v. 54, p. 64-85 (presidential address).
————, 1944, Meditations on granite. Part II: Geologists' Assoc. London Proc., v. 55, p. 45-93 (presidential address).
————, 1946, This subject of granite: Science Progress, v. 34, p. 659-669.
————, 1948a, Granites and granites, *in* Gilluly, James, chairman, Origin of granite: Geol. Soc. America Mem. 28, p. 1-19.
————, 1948b, A commentary on place in plutonism: Geol. Soc. London Quart. Jour., v. 104, p. 155-205 (presidential address).
————, 1949, A contemplation of time in plutonism: Geol. Soc. London Quart. Jour., v. 105, p. 101-156 (presidential address).
————, 1951, Metamorphism and granitisation: Geol. Soc. South Africa Trans., v. 54, annexure.
————, 1955, Granite series in mobile belts: Geol. Soc. America Mem. (in press).
Reed, J. C., 1937, The study of accessory minerals in igneous and metamorphic rocks: Am. Mineralogist, v. 22, p. 73-84.
Revelle, R., et al., 1955, Pelagic sediments of the Pacific: Geol. Soc. America Mem. (in press).
Scholtz, D. L., 1946, On the younger Precambrian granite plutons of the Cape Province: Geol. Soc. South Africa Trans. and Proc., v. 49, p. xxxv-lxxxii (presidential address).
Shand, S. J., 1947, Eruptive rocks, 3rd ed.: New York, John Wiley & Sons.
Shaw, D. M., 1954a, Trace elements in pelitic rocks. Part I, Variation during metamorphism: Geol. Soc. America Bull., v. 65, p. 1151-1166.
————, 1954b, Trace elements in pelitic rocks. Part II, Geochemical relations: Geol. Soc. America Bull., v. 65, p. 1167-1182.
Sindowski, F. K. H., 1949, Results and problems of heavy mineral analysis in Germany; a review of sedimentary petrological papers, 1936-1948: Jour. Sedimentary Petrology, v. 19, p. 3-25.
Smithson, Frank, 1937, Outgrowths on zircon in the middle Jurassic of Yorkshire: Geol. Mag., v. 74, p. 281-283.
————, 1939, Statistical methods in sedimentary petrology, pts. 1, 2, 3: Geol. Mag., v. 76, p. 297-309, 348-360, 417-427.
————, 1941, The alteration of detrital minerals in the Mesozoic rocks of Yorkshire: Geol. Mag., v. 78, p. 97-112.
————, 1942, The middle Jurassic rocks of Yorkshire; a petrological and paleogeographical study: Geol. Soc. London Quart. Jour., v. 98, p. 27-59.
————, 1950, The mineralogy of arenaceous deposits: Science Progress, v. 38, p. 10-21.
Strock, L. W., 1941, Geochemical data on Saratoga mineral waters, applied in deducing a new theory of their origin: Am. Jour. Sci., v. 239, p. 857-898.
Swart, B., 1950, Morphological aspects of the Bokkeveld series at Wuppertal, Cape Province: Univ. Stellenbosch Ann., v. 26, sec. A, p. 413-479.
Thoulet, J., 1913, Lithologie sous-marine: Inst. Océanographie Paris Ann., v. 5, fasc. 9, p. 1-14.
Thürach, H., 1884, Über das Vorkommen mikroskopischer Zirkone und Titanmineralien in den Gesteinen: Phys. Mediz. Ges. Würzburg, Verh., Band 18, no. 10, p. 203-284.
Tyler, S. A., Marsden, R. W., Grout, F. F., and Thiel, G. A., 1940, Studies of the Lake Superior Precambrian by accessory mineral methods: Geol. Soc. America Bull., v. 51, p. 1429-1537.
Walker, Frederick, and Mathias, Morna, 1947, The petrology of two granite-slate contacts at Cape Town, South Africa: Geol. Soc. London Quart. Jour., v. 102, p. 499-521.
Wasserstein, Benno, 1933, Zur Petrogenesis des Burgsandsteins zwischen Nürnberg und Weissenburg: Neues Jahrb., Beilage-Band 70, Abt. B, p. 335-392.
Young, E. J., 1954, Trace elements in recent marine sediments (abst.): Geol. Soc. America Bull., v. 65, p. 1329.
Zerndt, J., 1927, Mikroskopische Zirkone als Leitmineralien: Acad. polonaise sci. Bull. internat., sér. A, p. 363-377.

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UPWELLING AND THERMALLY ANOMALOUS PACIFIC COAST PLEISTOCENE MOLLUSCAN FAUNAS

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ABSTRACT. Many west North American marine mollusks have changed their geographic or bathymetric ranges since the Pleistocene. Some of these changes are explained here by assuming that contrasts in shallow-water temperature were greater at certain times during the Pleistocene than at present; there was a contemporaneous distribution of water which was both colder and warmer than is now normal along the west coast. As a result, forms now rather widely separated geographically or bathymetrically were able to live in close proximity and hence enter the fossil record together.

The distribution of water temperature that might be expected during the glacial ages under Simpson's hypothesis is used to illustrate this thesis. Cold waters were introduced by currents from ice-bound northern regions and commonly surfaced inshore as upwellings, while the temperature of shallow water unaffected by upwelling was raised as solar radiation increased. The ecologic composition of shallow-water Pleistocene molluscan assemblages would thus vary in a more or less predictable manner through the successive glacial and interglacial ages. Conditions invoked by glacial hypotheses other than Simpson's would result in similar faunal changes during the Pleistocene, though not to the same degree at the same times.

INTRODUCTION

The species that comprise the Pleistocene molluscan faunas of California and Baja California are largely still living; only a few forms appear to be extinct. Nonetheless, these faunas differ greatly in specific composition from the communities which live in coastal waters near the fossil localities today. The chief difference is due to important geographic and, locally, bathymetric changes in distribution among the Mollusca since the Pleistocene. The fossil faunas regularly contain a mixture of species which are now widely separated geographically; forms presently living only well to the north of a given fossil locality often are found associated with others that now occur far to the south. In addition, sediments that were deposited in shallow water occasionally contain species that live today only in moderately deep water at the latitude of the fossil locality. Thus species making up these molluscan faunas have withdrawn from part of their former ranges by migrating northward, or southward, or into deeper water. This peculiar intermingling of forms now widely separated geographically and ecologically has puzzled invertebrate paleontologists for many decades (see below).

During the course of my investigations of Pleistocene molluscan faunas from Baja California, similar anomalous mixtures were noted. Professor U. S. Grant suggested that the association might well be due to the influence of local cold-water upwelling on the distribution of northern and locally deep-water species during a period when near-shore sea-surface temperatures were high enough to support southern, warm-water species; a nearly similar view had been expressed earlier by Mason (1934, p. 105). A mechanism that might produce Pleistocene mixture of present-day cold- and warm-water forms was suggested to me by data presented recently by Arrhenius in his analysis of marine circulation as based on deep-sea core studies (1953, p. 189-201, esp. fig. 3.4.2, p. 199).

PALEOECOLOGY OF SOME PLEISTOCENE FAUNAS

Large Pleistocene molluscan assemblages contain species representing communities which lived in different habitats near the fossil locality. The area from which a given fauna was assembled depended largely upon the Pleistocene shoreline configuration and submarine topography near the site of deposition. Transportation of the ecologic components was accomplished chiefly by current action, wave action, and gravity. Evidence indicates that transport of even small shells laterally along a shallow-water coast is not possible for a great many miles (Handin, 1951, p. 46-53; Crowell, 1952, p. 70-73), and the depth from which shells may be brought into shallow water by storm waves probably does not exceed 20 fathoms (Woodring, 1946, p. 102). Since most of the fossils representing these Pleistocene assemblages obviously lived in near-association, it has been difficult to explain the occurrence in these faunas of species that now live geographically or bathymetrically well outside normal limits of transportation at a given locality. These shifts in ranges may be illustrated by an ecologic analysis of several Pleistocene faunas of the coast of Baja California and California.

Richly fossiliferous Pleistocene strata are well exposed in cliffs on the east side of Bahía San Quintín, Baja California. On the west side of the bay is a group of volcanic cones, the highest of which rises to 757 feet. When the San Quintín fauna was living, the shoreline was probably somewhat more than a mile to the east of the fossil locality, near the base of the first of a series of low cliffs which outline the present Plain of Santa Maria. The volcanic cones were then a group of islands which provided wave protection to the broad strait in which the fossiliferous sediments accumulated. Fossils from this locality have been listed by Dall (1921a, b), Orcutt, (1921a, b), Jordan (1926), and the writer (1954a). A large collection at the University of California, Los Angeles, made by Professor W. P. Popenoe and party in 1949, furnished data on the relative abundance of species.

Knowledge of the habitats of Pacific coast mollusks has greatly increased in recent years. Although still far from complete, it is adequate for generalized paleoecologic interpretation of Pleistocene assemblages. Information on present-day habitats of 179 of the 280 species known in the San Quintín fauna is available. Of these, 47 (26%) live in shallow-water habitats protected from waves, 46 (25%) in shallow water, exposed (chiefly rocky shore) sites, and 33 (19%) in shallow to moderately deep water offshore below strong wave action. The remaining 53 (30%) range more widely ecologically, living in a variety of protected and exposed habitats. Species represented in the San Quintín fauna by the greatest numbers of individuals live today in shallow-water protected habitats, or are tolerant of such environments. Relatively few specimens represent species which now inhabit exposed or offshore sites. Protected shallow-water forms probably lived where they are found, in the lee of the volcanic islands. Shallow-water exposed coast forms must have been derived from the exposed sides of the islands, which accounts for their presence in great variety but in small numbers. Of the 268 species known to be living, 49 (18%) live only to the north, and 10 (4%) only south of the bay; the present ranges of the species are shown in figure 1. Most of the northern

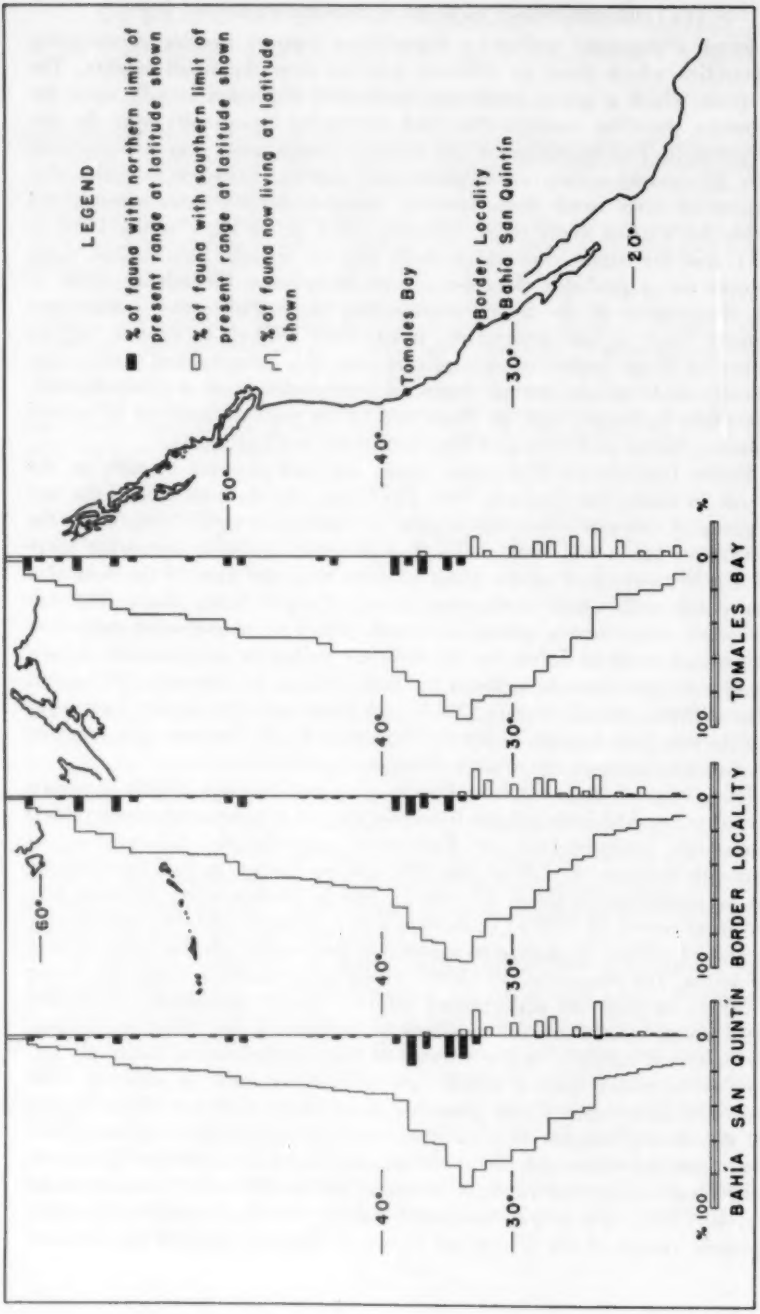

Fig. 1. The recent distribution of molluscan species present in the Pleistocene deposits at Bahía San Quintín, at the Border locality, and at Tomales Bay.

species are shallow-water exposed-coast or offshore forms, while most of the southern species live in protected shallow-water environments.

Several outcrops of a fossiliferous Pleistocene bed exposed in the extreme southwestern corner of the United States have been collectively termed the "Border locality" by Emerson and Addicott, who made a careful ecologic analysis of the fauna (1953). They concluded that the fauna either lived in an embayment or was sub-tidal along an outer coast. Recent field work indicates the latter view is more tenable, for deposition occurred on a wave-cut terrace correlative with the Nestor terrace (Ellis and Lee, 1919, p. 25-29, pl. 6). The position of the base of the cliffs at the rear of the terrace platform places the locality about one-half mile seaward of the former coast, and limits the water depth to about 10 fathoms. The fauna of 110 species includes 15 known living to the north only, but most of these are known in the San Diego Bay region (fig. 1). The 3 most northern species are shallow-water exposed-coast or offshore forms. One species (*Fusitriton oregonensis*) is not now known to live at less than 80 fathoms off southern California (Woodring, 1946, p. 90).

Many other Pleistocene deposits contain species which are geographically or bathymetrically separated today. These include: (a) unnamed terrace deposits at Punta Baja and in the Punta Descanso region, and between Rosarito Beach and the International Boundary, Baja California (Valentine, 1954a); (b) terrace deposits at Newport Beach, California (U.C.L.A. collections; the fauna is currently being studied by Mr. George P. Kanakoff, Los Angeles County Museum); (c) the Lomita marl, Timms Point silt, San Pedro sand, Palos Verdes sand, and unnamed terrace deposits in the Palos Verdes Hills, California (Woodring, 1946, p. 87-90); (d) sands in the Baldwin Hills, California, which have been correlated with the Palos Verdes sand (G. Willett, 1937); (e) sands in Potrero Canyon, Pacific Palisades, California, also correlated with the Palos Verdes sand (Woodring, in Hoots, 1931, p. 121-122; F. C. Clark collection, U.C.L.A.); and (f) the Millerton and Tomales formations, Tomales Bay region, California (Dickerson, 1922; Mason, 1934; Weaver, 1949, p. 99-105).

The Tomales Bay deposits are notable, for they contain a forest flora which includes species which live today only north of the fossil localities (Mason, 1934). By contrast, in the associated molluscan fauna 16 (43%) of the 37 species live to southward, with 4 of these not ranging north of Santa Barbara today[1] (see fig. 1).

POSSIBLE CAUSES OF FAUNAL REDISTRIBUTION

Explanations previously proposed.—Several explanations have been advanced for the anomalous ranges. Smith (1919) thought that successive northern and southern shifts of isotherms during the Pleistocene would account for the redistribution, though this fails to allow for the presence of both northern and southern species at the same locality. Crickmay (1929) ascribed the mixing to the reworking of fossils from sediments deposited while the sea

[1] A single species is reported to live only north of Tomales Bay (*Glycimeris septentrionalis*). Since this species has often been misidentified (G. Willett, 1944), verification of both its Recent and fossil records is desirable.

temperature was warmer or cooler. That this occurred consistently all along the entire coast seems doubtful. Gale (Grant and Gale, 1931, p. 39, 64) reasoned that a land barrier north of the San Pedro area might have protected that region from cold northern waters in the Pleistocene, allowing immigration of warm-water species. Determinants of the limits of range are probably often imposed by coastal topography and its ecologic effects, so that small changes of ranges may result as coastal outlines are modified. Pleistocene range changes of hundreds of miles, however, cannot be ascribed to topographic changes alone. Further, recent studies have shown that the water south of such a barrier may be cold (see below). Woodring (1946, p. 102) has discussed and rejected the effects of local temporary changes in ocean temperatures as not adequate to produce lasting changes in faunal distribution.

The possibility that evolutionary changes in the physiology and therefore ecologic requirements of species have enabled them to alter their environments also has been considered by Woodring (1946, p. 102, 103; 1951). This is certainly possible for a few species, but such changes in large numbers of forms appear improbable. Perhaps some of the apparent range alterations are due to the elimination of ecotypic races living outside of the range of the surviving species, as suggested by Axelrod (1941) to explain the anomalous occurrences of some Late Tertiary fossil plants in habitats in which similar species do not now live. Woodring has suggested that a similar explanation might be applied to the Mollusca (1951). Again, this may have been a contributing factor, but that all these anomalous ranges are to be attributed to ecospecies does not seem likely.

Taken together, all these explanations seemingly fail to account for the large scale and widespread occurrence of the faunal redistributions observed. It is believed that a near-contemporaneous distribution of both warmer and colder water than is normal today along the coast of California and Baja California is clearly required at times during the Pleistocene (Valentine, 1954b).

Evidence from the present distribution of marine life.—Present-day anomalies in the distribution of marine organisms along the Pacific Coast are well known. Certain species are found north of their expected ranges in the warm waters of embayments, while other forms living in or near upwellings of cold water occur south of latitudes which they normally inhabit. For example, Hubbs (1948, p. 460-462) reports fish common to the south living in Elkhorn Slough, Tomales Bay, and Morro Bay in central California, often with no known intermediate stations. Conversely, relatively northern, cold-water fish common in central California waters are found along the Baja California coast in areas of upwelling. Hubbs also records bathymetrically anomalous occurrences of invertebrates; an abalone (*Haliotis rufescens*) and a sea urchin (*Strongylocentrotus franciscanus*), both of which live today only offshore in cooler waters near San Diego, occur intertidally in areas of upwelling in Baja California. Burch (1946, no. 57, p. 6) cites a similar occurrence at Punta Banda, Baja California, where a group of invertebrate species (including the limpet *Acmaea mitra*) which are normally offshore types at

this latitude is found in the littoral zone near upwellings on the south side of the point. On the north side, a relatively warm-water invertebrate fauna, which included *Acanthina lugubris*, was collected.

Correlations between marine algae and the distribution of upwelling waters have been made by Dawson, who found relatively cold-water species living in areas of upwelling far to the south of their expected ranges (1951). In a later study, Dawson was able to relate the occurrence of both indigenous warm-water forms and somewhat exotic cold-water species in Bahía Vizcaino, Baja California, to the presence of water transported by an eddy current from areas of upwelling off the coast (1952). He states in summary that "temperature conditions along the coastal margin of the clockwise eddy within Bahía Vizcaino are so varied that distinctive and dissimilar [relatively warm- and cold-water] intertidal marine floras occur in close proximity."

There is every reason to suppose that similar patterns of distribution existed during the Pleistocene. The present ranges of Mollusca seem to be determined chiefly by ocean temperature. Since their ranges are commonly expressed in terms of latitude, unusual northern or southern occurrences of species made possible by the irregular distribution of water temperatures along the coast are masked by being included in the total range record. To change or extend the present total ranges of species to include their Pleistocene records would require an exaggeration and extension of the present pattern of water temperature distribution. Using the present distribution of species (and water temperature) as a datum, it appears that waters near certain Pleistocene localities were at least in part warmer and cooler, or had a greater temperature range, than waters near these localities today.

In regions in which the difference between present-day summer and winter water temperature is great, warm-water types which spawn in summer are sometimes associated with cold-water types which spawn in winter (Hutchins, 1947; Eckman, 1953, p. 112-114). I am greatly indebted to Professor Carl L. Hubbs, who has drawn on his wide knowledge of the distribution of organisms and of water temperatures in the eastern Pacific to point out that this phenomenon occurs rather commonly along the northwest American coast. Dr. Hubbs (in litteris) cites the northern part of the Gulf of California and Bahía Magdalena as two localities where relatively warm- and cold-water species which spawn in summer and winter, respectively, are now closely associated, and suggests that this factor may account in part for the anomalous associations in Pleistocene faunas. If we use the present species distribution as a datum, contemporaneous range extensions of southern species northward and northern species southward during the Pleistocene would still have required somewhat greater seasonal extremes of water temperatures than are present today.

Evidence from the present distribution of near-shore water temperatures.—Relatively cold southern and Baja California coastal waters are introduced in part by southeastward-flowing currents, driven by north and northwesterly winds. During the spring and summer months, a northward-flowing countercurrent may appear at the surface, landward of the southward-flowing currents, bringing relatively warm water from the south. The relation of the

countercurrent to winds and to other currents is not fully understood; Sverdrup et al. discuss countercurrents briefly (1942, p. 725-727), and Manar (1953, p. 9-13) gives some recent information on the countercurrent off California.

The causes of present-day cold-water upwelling along the west American coast are better known, and have been summarized by Sverdrup et al. (1942, p. 500-503). The north and northwesterly winds cause an offshore transport of surface water, due to the interaction of frictional forces and the Coriolis parameter. Deeper, cooler waters well-up near shore to replace the relatively warm water thus removed. The depth from which such upwelling originates is probably not much greater than 100 fathoms (Sverdrup and Fleming, 1941, p. 332-334). The intensity of the upwelling is related to wind velocity and to the configuration of the ocean floor and coast line. Upwelling may also occur when warm surface waters are driven away from the south sides of points by northerly or northwesterly winds, or are blown offshore by easterlies. Figure 2 shows areas in which upwelling is known to occur at present off the coast of California and Baja California (after Manar, 1953). The presence and intensity of upwelling varies from time to time and from place to place, depending upon wind conditions and topography.

The nature of water temperatures and the influence of upwelling along the coast today is indicated by data assembled during the course of researches by the Alan Hancock Foundation, University of Southern California. Acknowledgment is due Dr. Robert E. Stevenson and Mr. Donn S. Gorsline, who have generously furnished information on the distribution of present-day water temperatures along the coast. The highest surface-water temperatures are recorded in lagoons, where they commonly reach 90°F. on hot days. By contrast, representative records in offshore waters indicate that surface temperatures were lowered 9°F. by upwelling during July (73° to 64°), 5°F. during October (66° to 61°), and about 3°F. in December (63.5° to 60.6°), 1954. The influence of upwelling during periods of increased solar radiation is well illustrated by the increased temperature differential along the California coast during summertime today.

Present-day, near-shore temperature distribution is thus quite irregular when viewed in detail; relatively cold waters are derived chiefly from southward-flowing currents and from upwellings, while relatively warm waters may result from solar heating of shallow waters in protected regions, or may be introduced by northward-flowing countercurrents. It is necessary only to postulate an intensification of these conditions and processes, which occur along the Pacific coast today, to explain much of the Pleistocene and post-Pleistocene faunal redistribution.

PLEISTOCENE FAUNAL CHANGES AS ILLUSTRATED WITH SIMPSON'S GLACIAL HYPOTHESIS

Many attempts have been made to explain Pleistocene glaciation. None of the glacial hypotheses yet proposed has accounted for all aspects of the intricate pattern of Pleistocene climatic conditions required by empirical and theoretical evidence. Perhaps the best-known hypothesis is that of Simpson

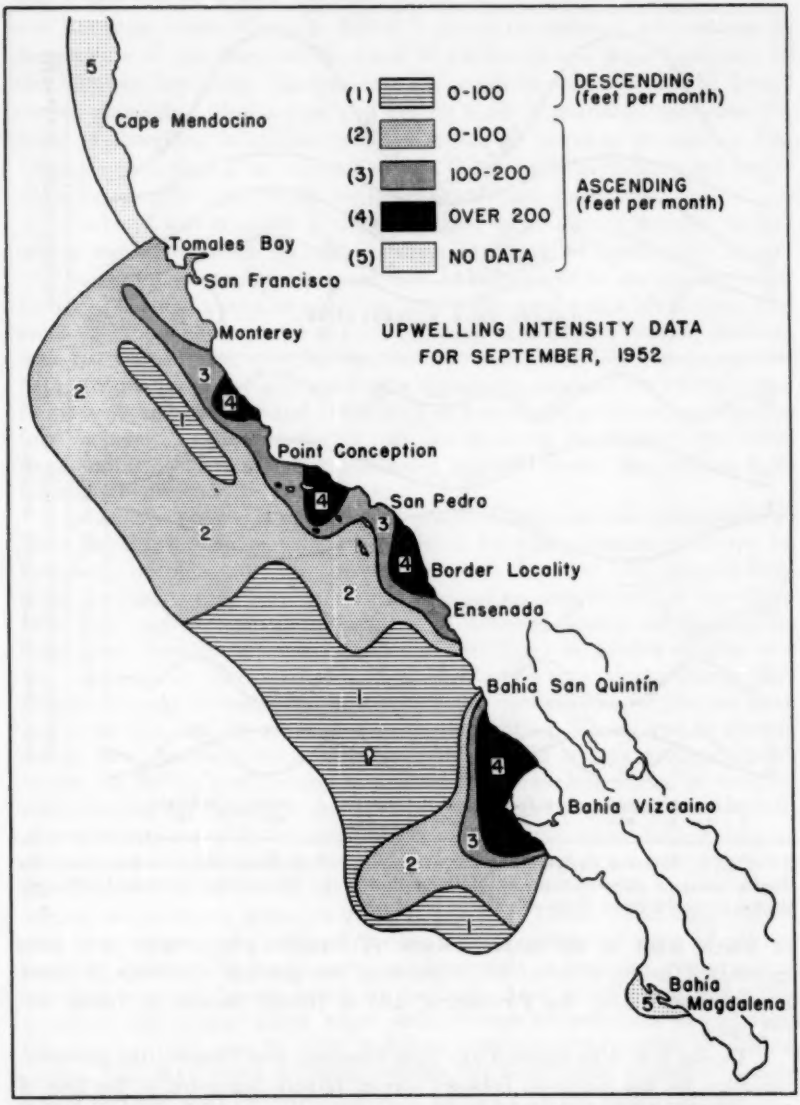

Fig. 2. Distribution and intensity of upwelling along the coast of California and Baja California. Data on the upwelling intensity north of San Francisco and at Bahía Magdalena are not available (after Manar, 1953).

(1934, 1940); it has many merits, but some objectionable features as well. Good reviews of Simpson's and of other glacial hypotheses are given by Flint (1947, p. 501-520) and by H. C. Willett (1949). The useful, graphic form

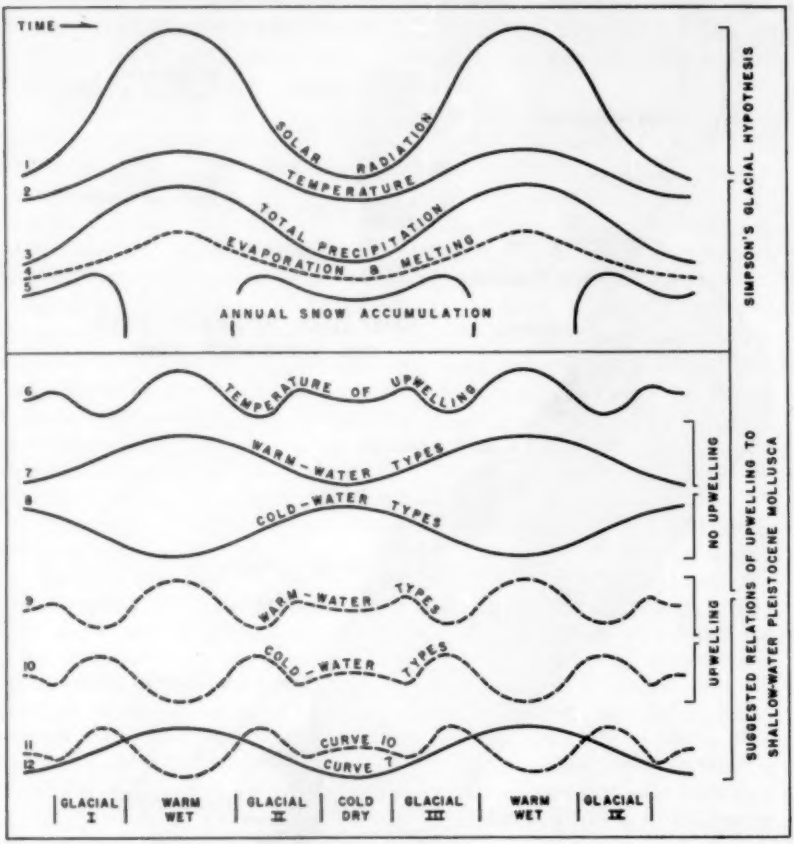

Fig. 3. Inferred variation in the availability of shallow marine water along the Pacific coast to different types of Mollusca during the Pleistocene, illustrated with conditions proposed under Simpson's glacial hypothesis.

in which many of the major features of Simpson's hypothesis have been epitomized makes it ideal for illustrating the possible character of water temperatures during the Pleistocene, and of related changes in faunal distribution.

Curves 1 to 5 in figure 3 are after Simpson, and illustrate the interrelationships he has proposed between several factors important to the line of his argument. The intensity of atmospheric and oceanic circulation and of upwelling, not represented in the figure, would presumably vary proportionately with solar radiation. The southward drift of cold water along the California coast would probably be accelerated during glaciation. Further, during glaciation this water probably was colder than at present, especially at shallow depths, due to effects of lowered temperatures in the North Pacific region,

and to dilution by glacial meltwaters from the ice-covered western Alaskan and Canadian coasts. Curve 6, figure 3, shows the inferred relationships of temperature of upwelling off the coast of California and Baja California to the Simpson hypothesis. Temperature of upwelling water should be lowest during glaciation, when a supply of coldest water is available, and when the vigor of upwelling is comparatively great due to increased storminess. Upwelling waters should be warmest during the warm interglacials, and somewhere between the extremes during the cold interglacial age.

Curves 7 and 8, figure 3, show the effect of conditions depicted in preceding curves on faunas living in shallow waters where upwelling is absent. The height of a curve at any point may be interpreted as the relative availability of shallow waters to warm- or cold-water species at a given time. The numbers of southern species capable of living at any given locality increase with the temperature, whereas the northern cool-water forms decrease. Exposure of shallow-water communities to upwellings produces the effects shown in curves 9 and 10. Potential availability of a region to southern, warm-water forms increases as the temperature rises, but decreases in periods of glaciation or of falling temperature. For cold-water northern forms, the reaction is in the opposite direction.

In a given region, immigration of progressively more southern species as warm waters develop may be accomplished by transportation of larvae by longshore, counter and eddy currents. In much the same way, progressively more northern forms may migrate southward as temperature of upwelling falls. The greatest temperature contrast is achieved during the glacials. At these times near-shore waters should be distributed in patches of high and low temperatures, with intermediate temperatures where mixing occurs. Distribution would be controlled in detail by the configuration of the sea floor and coast line, and by seasonal climatic fluctuations. Warm- and cold-water species hardy enough to achieve migration would occupy ecologic niches locally vacated by stenothermal members of the preceding fauna, or compete with eurythermal forms for appropriate sites. Such competition would probably eliminate many of the immigrants; others would successfully replace or coexist with eurythermal species. Most species living in or near upwelling waters would be cold-water, exposed-coast forms, while most species which inhabit environments protected from strong wave action would be protected also from cold-water upwellings. Shallow-water stenothermal types adapted to water of intermediate temperatures might survive in localities where mixing of waters occurred. Species which are eurybathyal but stenothermal, and which withdraw into deeper water when shallow-water temperatures exceed their tolerances, would now be able to follow cold upwelling waters to shallow depths. That they would do so is probable, for food supply in shallow waters would increase with the introduction of nutrients by the rising currents.

At any given locality, the composition of the molluscan community should vary somewhat cyclically through the succession of glacial and interglacial Pleistocene ages. This is illustrated in figure 3, where curves of faunas living in waters where upwelling is present (curve 11) and absent (curve 12) are superimposed. Pleistocene glacial-stage faunas in regions where temperature

extremes are represented should contain southern species of mostly protected environments, and northern species of mostly exposed coast or offshore habitats. The first and third interglacial stages would be characterized by warm-water forms, in addition to eurythermal and intermediate-temperature species, and the second interglacial by mostly eurythermal and intermediate-temperature types. The symmetry of the curves, dictated by the rigidity of the qualitative, graphic presentation, is not to be expected in nature.

ADDITIONAL CONSIDERATIONS AND SUMMARY

The distribution of highs and lows on curves 6 to 12 in figure 3 is dependent upon the relations of solar radiation, atmospheric circulation, and oceanic circulation to the glacial and interglacial ages. The curves will be modified if the relations inferred under Simpson's hypothesis prove invalid. Arrhenius' data seem to show that 4 instead of 2 major maxima of oceanic circulation occurred during the Pleistocene (1953, p. 199). If this is true, 4 maxima of solar radiation may account for the 4 glacial ages, as advocated by H. C. Willett (1949), and discussed by Bell (1953). Even under such conditions, it is believed that glacial-age faunas would still have shown the greatest temperature contrasts.

The degree to which warm countercurrents might have affected the distribution of Pleistocene water temperature cannot be determined at present. Their potentialities should be investigated, however; an increase in solar heat in the atmosphere or at the Earth's surface is not a necessary corollary of an increase in atmospheric circulation, and countercurrents may prove to have been an important source of warm water at times during the Pleistocene. They may also be capable of transporting the larvae of warm-water species northward.

The preceding speculations are intended to show that Pleistocene changes in the distribution of water temperature might be correlated with changes in Pleistocene molluscan faunas so far as their composition is concerned. A periodic expansion of warm water would enable some types now restricted by thermal barriers to range farther north, whereas increased upwelling of colder waters would enable more northern species to extend farther south. This narrowing and intensifying of the ecologic zones would bring into close association types which are now widely separated, and permit them to enter the record contemporaneously. Herein may well lie the explanation for the anomalous Pleistocene faunal associations.

Verification of this proposition is difficult, but additional evidence will appear as the Pleistocene faunas of western North America become better known. Fortunately, Pleistocene molluscan assemblages are commonly rather large, and are assumed to provide a statistically adequate sample of the fauna they represent. Although the evidence which has led to the postulates presented above is based on marine mollusks, it is felt that other classes of marine organisms containing stenothermal species may well show the same response to processes operating during the Pleistocene.

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REFERENCES

Arrhenius, Gustaf, 1953, Sediment cores from the east Pacific: Repts. Swedish Deep-Sea Exped., 1947-1948, v. 5, fasc. 1.

Axelrod, D. I., 1941, The concept of ecospecies in Tertiary paleobotany: Nat. Acad. Sci. Proc., v. 27, p. 545-556.

Bell, Barbara, 1953, Solar variation as an explanation of climatic change, *in* Shapley, Harlow, ed., Climatic change: Cambridge, Harvard Univ. Press, p. 124-136.

Burch, J. Q., ed., 1945-46, Distributional list of the west American marine mollusks from San Diego, California to the Polar Sea: Conch. Club Southern California Minutes, pt. 2, v. 2, Gastropoda in part, pagination by issue.

Crickmay, C. H., 1929, The anomalous stratigraphy of Deadman's Island, California: Jour. Geology, v. 37, p. 617-638.

Crowell, J. C., 1952, Submarine canyons bordering central and southern California: Jour. Geology, v. 60, p. 58-83.

Dall, W. H., 1921a, New fossil invertebrates from San Quentin Bay, Lower California: W. Am. Scientist, v. 19, p. 17-18.

————, 1921b, New shells from the Pliocene or early Pleistocene of San Quentin Bay, Lower California: W. Am. Scientist, v. 19, p. 21-23.

Dawson, Y. E., 1951, A further study of upwelling and associated vegetation along Pacific Baja California, Mexico, Jour. Marine Research, v. 10, p. 39-58.

————, 1952, Circulation within Bahia Vizcaino, Baja California, and its effects on marine vegetation: Am. Jour. Botany, v. 39, p. 425-432.

Dickerson, R. E., 1922, Tertiary and Quaternary history of the Petaluma, Point Reyes and Santa Rosa Quadrangles: California Acad. Sci. Proc., 4th ser., v. 11, p. 527-601.

Eckman, Sven, 1953, Zoogeography of the sea: London, Sidgwick and Jackson.

Ellis, A. J., and Lee, C. H., 1919, Geology and ground waters of the western part of San Diego County, California: U. S. Geol. Survey Water-Supply Paper 446.

Emerson, W. K., and Addicott, W. O., 1953, A Pleistocene invertebrate fauna from the southwest corner of San Diego County, California: San Diego Soc. Nat. History Trans., v. 11, p. 429-444.

Flint, R. F., 1947, Glacial geology and the Pleistocene epoch: New York, John Wiley & Sons.

Grant, U. S., IV, and Gale, H. R., 1931, Catalogue of the marine Pliocene and Pleistocene Mollusca of California and adjacent regions: San Diego Soc. Nat. History Mem., v. 1.

Handin, J. W., 1951, The source, transportation, and deposition of beach sediment in southern California: U. S. Army Corps Engineers, Beach Erosion Board Tech. Mem. 22.

Hoots, H. W., 1931, Geology of the eastern part of the Santa Monica Mountains, Los Angeles County, California: U. S. Geol. Survey Prof. Paper 165-C, p. 83-134.

Hubbs, C. L., 1948, Changes in the fish fauna of western North America correlated with changes in ocean temperature: Jour. Marine Research, v. 7, p. 459-482.

Hutchins, L. W., 1947, The bases for temperature zonation in geographical distribution: Ecol. Mon., v. 17, p. 325-335.

Jordan, E. K., 1926, Molluscan fauna of the Pleistocene of San Quentin Bay, Lower California: California Acad. Sci. Proc., 4th ser., v. 15, p. 241-254.

Manar, T. A., ed., 1953, Progress report, 1 July 1952-30 June 1953: California Marine Res. Comm., California Cooperative Sardine Research Program.

Mason, H. L., 1934, Pleistocene flora of the Tomales formation: Carnegie Inst. Washington Pub. 415, p. 81-180.

Orcutt, C. R., 1921, Paradise lost: W. Am. Scientist, v. 19, p. 18-19.

————, 1921b, Pleistocene beds of San Quentin Bay, Lower California: W. Am. Scientist, v. 19, p. 23-24.

Simpson, G. G., 1934, World climate during the Quaternary period: Royal Meteorol. Soc. Quart. Jour., v. 60, p. 425-478.

————, 1940, Possible causes of change in climate and their limitations: Linnean Soc. London Proc., v. 152, p. 190-219.

Smith, J. P., 1919, Climatic relations of the Tertiary and Quaternary faunas of the California region: California Acad. Sci. Proc., 4th ser., v. 9, p. 123-173.

Sverdrup, H. U., and Fleming, R. H., 1941, The waters off the coast of southern California, March to July, 1937: Scripps Inst. Oceanography Bull., tech. ser., v. 4, p. 261-378.

Sverdrup, H. U., Johnson, M. W., and Fleming, R. H., 1942, The oceans: New York, Prentice-Hall, Inc.

Valentine, J. W., 1954a, Pleistocene paleontology of a portion of the northwest coast of Baja California, Mexico (unpublished): Master of Arts thesis, Library, Univ. California, Los Angeles.

————, 1954b, Ecologic requirements and depositional environments of Pleistocene molluscan faunas from southern and Baja California (abst.): Jour. Paleontology, v. 28, p. 881.

Weaver, C. E., 1949, Geology of the Coast Ranges immediately north of the San Francisco Bay region, California: Geol. Soc. America Mem. 35.

Willett, George, 1937, An upper Pleistocene fauna from the Baldwin Hills, Los Angeles County, California: San Diego Soc. Nat. History Trans., v. 8, p. 379-406.

————, 1944, Northwest American species of Glycimeris: Southern California Acad. Sci. Bull., v. 42, p. 107-114.

Willett, H. C., 1949, Long-period fluctuations of the general circulation of the atmosphere: Jour. Meteorology, v. 6, p. 34-50.

Woodring, W. P., 1951, Basic assumption underlying paleoecology (abst.): Science, v. 113, p. 482-483.

————, *in* Woodring, W. P., Bramlette, M. N., and Kew, W. S. W., 1946, Geology and paleontology of Palos Verdes Hills, California, U. S. Geol. Survey Prof. Paper 207.

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THE ORIGIN AND SIGNIFICANCE OF PRAIRIE MOUNDS

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ABSTRACT. Locally, the ground moraine of the western prairies is covered with till mounds. The mounds—which from the air resemble giant doughnuts—average 300 feet in diameter and 15 feet in height, and in most cases have a central depression which lies 3 to 4 feet lower than the outer rim of the mounds. It is believed that the mounds originated as debris-filled pits on a stagnant ice surface and that the melting of the ice left the pit fillings as mounds. The mounds and associated features over parts of western Canada are probably related to slow wastage of the ice in a downslope direction.

INTRODUCTION

In the course of mapping the glacial deposits of an area in east-central Alberta it was noted that, locally, the ground moraine is covered with mounds which from the air resemble giant doughnuts. A well-developed field of mounds, covering some 25 square miles, is found 14 miles east of Hemaruka in Tp. 32, R. 6, W. of the 4th Meridian. A few mounds occur 4½ miles east of the town of Veteran on the southwestern edge of the Viking moraine. Aerial photographs of parts of the Red Deer area in Alberta and of the Coteau moraine in Saskatchewan show mounds which appear identical to those in east-central Alberta. Similar mounds have been found in the Watino area of northwestern Alberta and are described by Henderson (1952).

Only a small part of western Canada has been subjected to detailed glacial studies, and it is quite possible that when more areas are examined these mound fields may well rival drumlins as a major feature of glaciated regions.

DESCRIPTION OF MOUNDS

Aerial views of prairie mounds (pl. 1-A) show that they are nearly circular and in most cases have a central depression. The mounds average 300 feet in diameter and 15 feet in height. The central depression is generally 3 to 4 feet lower than the elevation of the outer rim of the mounds.

For the most part the mounds are composed of clayey till. An exception to this general rule is found, however, in the mounds which exist on the southwestern border of the Viking moraine. At this location several mounds were found which are formed primarily of till but contain masses of contorted and slumped stratified silts and clays (fig. 1). It is significant to note that similar inclusions of stratified sediments have not been found in the ground moraine adjacent to the mound fields.

The intermound trenches are quite flat except where the mounds occur on the edges of, or in areas of, recessional moraine. Drilling operations in the mound field east of Hemaruka showed that the mounds and the intermound trenches are underlain by a minimum of 40 feet of clayey till. With the exception of a 3-foot layer of silty till cover on the rim of the mounds, there was no difference noted between the till in the mounds and the till in the intermound trenches.

In some places the intermound trenches are covered with a thin layer of sand which contains a few pebbles and shows evidence of rude sorting. This veneer of sand is not confined to the mound areas but is found over much of the ground moraine of east-central Alberta.

The mounds in the Watino area of Alberta, described by Henderson (1952), are only 5 to 10 feet in height, but the diameters are approximately the same as those found in east-central Alberta. The Watino mounds are composed largely of till, and the intermound spaces are covered with a layer of silt 2 to 3 feet in depth.

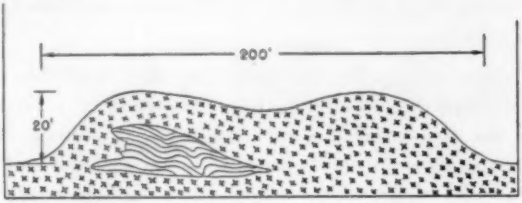

FIG. 1

Clayey till

Contorted sand, silt and clay

Highway cut showing cross section of mound - Lsd. 13, Sec. 12, Tp. 35, R. 8, W. of 4th. meridian.

ORIGIN OF MOUNDS

The size and composition of the mounds make it seem logical that they must be ice-depositional features of some type. Observations of present-day stagnant ice zones on valley glaciers reveal the presence of a wide variety of forms and deposits which include a superglacial cover of sorted and unsorted debris, and large pits which are frequently water filled and contain sediments of a sorted and unsorted nature. Applying these observations to stagnant continental ice sheets, it is believed that under conditions of slow melting the pits would be filled mainly with unsorted material, and when the ice completely melted this unsorted debris would be left as a mound.

Two methods are suggested for the formation of these pits. The first method (fig. 2, stage 1) suggests that through ablation debris will be distributed heterogeneously on the ice surface. Due to the insulation effects of the debris, the ice will melt more rapidly in those areas where the debris is thinnest, and as a result pits form. Crosby (1902) explained the deepening of the water-filled pits on the Malaspina glacier by convection-current action. This method of deepening continues as long as the debris in the base of the pits is permeable and allows the transfer of heat from the water to the ice. Holmes (1947) suggested that where the debris is clayey in nature, the clayey material in the base of the pits will effectively insulate the underlying ice and thus inhibit deepening by convection currents.

As the till in east-central Alberta has a high clay content, an alternate mode of formation of the pits is offered (fig. 2, stage 1A). In many respects a stagnant ice sheet is similar to a limestone formation, and it is not unlikely

that caves would form below the water-table in stagnant ice by the enlargement of crevasses or by more rapid solution of those sections in the ice which contain lesser amounts of debris. Collapse of the cave roofs would lead to the formation of "ice-sinks" or pits. With regard to this analogy between a limestone region and stagnant ice, it is interesting to note the similarity between a field of prairie mounds (pl. 1-A) and an area of sink-hole topography (pl. 1-B). If we take into account differences in scale, the area of sink-hole topography appears as a mirror image of the region of prairie mounds.

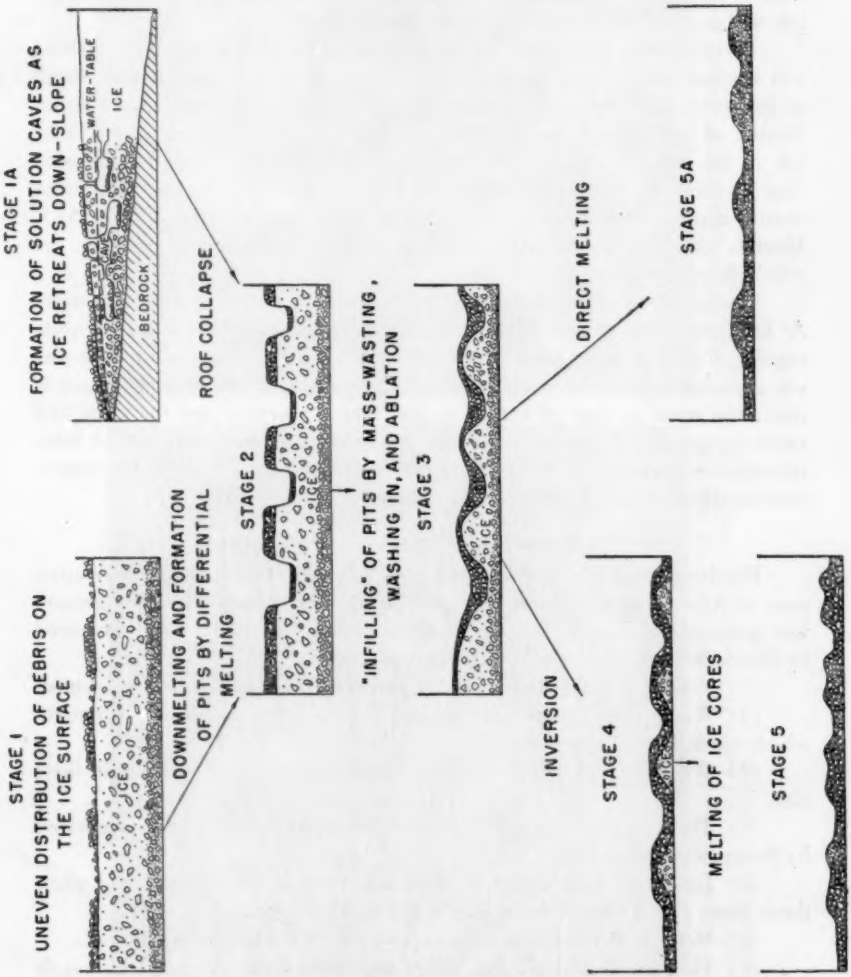

Fig. 2. Diagram to show formation of mounds during final stages of stagnation of an ice sheet.

In discussing superglacial debris on the stagnant end of the Wolf Creek glacier in the Canadian Yukon, Sharp (1949) stated: "The higher a feature becomes the more thinly spread is its debris mantle and simultaneously the mantle on the low areas becomes thicker by additions from surrounding areas and to some extent by residual accumulation from the melting ice." If this principle is applied to a pitted ice surface, the debris which lies on the high areas will move into the pits by being washed in and through mass-wasting (fig. 2, stage 3). The pit deposits will be a mixture of sorted and unsorted debris. If melting is very slow on the ice surface, most of the debris in the pits will probably be unsorted material, that is, till.

As the debris moves off the high areas and settles in the pits, melting will become more rapid on the high areas. If there is a considerable depth of ice below the base of the pits, continued downwasting may lead to an inversion of topography. In such a case (fig. 2, stage 4) an ice core will be left in the mound which, upon melting, will produce a central depression (fig. 2, stage 5). If the ice below the pits is quite thin, mounds without a central depression will occur as a result of direct melting (fig. 2, stage 5A). Mounds which do not contain a central depression are found, but they are relatively uncommon.

The apparent regularity of the mound pattern deserves some attention. At first glance the mound dimensions and intermound distances appear quite regular. However, upon closer examination it is evident that these parameters are apparent rather than real. Indeed, the regularity of the mound pattern is much the same as that of kettles in the Viking moraine and the swell and swale topography of many parts of the surrounding ground moraine. All these features are probably related to crevasses in the stagnant ice and to the heterogeneous distribution of debris within the ice.

ORIGIN OF MOUNDS AS PROPOSED BY HENDERSON

Henderson (1952) believed that the till mounds found in the Watino area of Alberta were formed in a periglacial environment when the ground was permanently frozen. The mode of formation of the mounds as advanced by Henderson can be summarized as follows:

(1) Frozen ground contracts and polygonal tension cracks are formed.

(2) Water then enters the cracks, and on freezing forms ice wedges which cause their enlargement.

(3) Water migrates to the ice wedges and produces an increase in their size.

(4) The centers of the polygons are bulged by lateral pressures exerted by the growing ice wedges.

(5) Ice lenses form under the bulged centers of the mounds, and when these lenses melt a central depression is left in the mounds.

(6) Melting of the ice wedges accentuates the relief of the mounds.

(7) Thin silts found over the till in the intermound spaces are the result of recent drainage.

PLATE 1

B. Sinkhole plain, Harrison County, Indiana. (Photograph by CSS-USDA.)

A. Prairie mounds—Tp. 32, R. 6, W. of the 4th Meridian. (Reproduced with the permission of the Technical Division, Dept. of Lands and Forests, Alberta.)

The above theory is attractive in that it utilizes observations made on the mounds found in the Arctic. However, there are certain objections to the above theory which may be outlined as follows:

(1) It fails to account for stratified sediments found in some of the mounds.

(2) Clayey tills are relatively impermeable and it is doubtful if much water would migrate to the ice wedges. Rather it might be expected that mounds would be more plentiful on silts and more permeable materials. All the mounds examined by the writer are composed essentially of till.

(3) No evidence of ice-wedge fillings in the intermound spaces has been found.

(4) Mounds found in Arctic regions are usually much smaller than those under consideration, and many of the Arctic mounds are formed primarily of ice which upon melting does not leave an earth mound.

(5) If the mounds are formed mainly by lateral displacement of till by ice wedges, then the volume of mounds must approximately equal the volume of the ice wedges. Consequently, an ice wedge which has a depth of 20 feet would have to be about 500 feet wide at the surface in order to produce a mound which is 300 feet in diameter and 15 feet in height. Even though, as Henderson (1952) suggests, the mounds may owe part of their relief to the upheaval of plastic clay generated by freezing of a thawed layer over permanently frozen ground and to solifluction in the intermound trenches, the dimensions of the ice wedges still would seem unreasonably large.

SIGNIFICANCE OF MOUNDS

Johnston and Wickenden (1931) and later Bretz (1943) noted that outwash materials are relatively rare on the Canadian prairies. To account for this phenomenon, Johnston and Wickenden (1931) suggested that the wastage of the ice was largely by evaporation. Dry, westerly flowing winds would aid in this type of wastage. The absence of outwash means that the englacial debris must have been deposited in some other form. It is believed that the till mounds account for a small part of this englacial material.

The rest of the englacial debris is probably represented in a thin layer of sand and pebbles which overlies much of the ground moraine in east-central Alberta. This sand varies from 1 to 5 feet in thickness and commonly overlies the B2 horizon of solidized solonetz soil profiles. In some places this sand shows rude stratification which is probably the result of temporary stream action on the stagnant ice.

The fact that the retreat of the ice in east-central Alberta was generally in a downslope direction may have an important bearing on the lack of outwash, the formation of mounds and the thin surficial sands. Under conditions of downslope retreat, lakes would form in front of the ice, and meltwater action would be cut down considerably except under local conditions. A water-table could be built up in the stagnant ice and this would lead to the formation of solution caves and hence mounds.

The lack of eskers in east-central Alberta may well be a result of this downslope retreat. However, in the Vermilion area long intersecting esker-like ridges of till have been found. These have been interpreted by Bayrock (1954) as ice-block ridges (crevasse-fillings of till between stagnant ice blocks). In effect, these ridges are similar in origin to the till mounds except that a crevasse is involved instead of a pit.

It is believed that if these two concepts of slow melting (perhaps by evaporation) and downslope retreat are kept in mind, many of the enigmas of glacial geology in western Canada may well be answered.

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REFERENCES

Bayrock, L. A., 1954, Glacial geology of an area in east-central Alberta: M.Sc. thesis, Univ. of Alberta.

Bretz, J H., 1943, Keewatin end moraines in Alberta: Geol. Soc. America Bull., v. 54, p. 31-52.

Crosby, W. O., 1902, Origin of eskers: Am. Geologist, v. 30, p. 1-38.

Henderson, E. P., 1952, Pleistocene geology of the Watino quadrangle, Alberta: Ph.D. thesis, Indiana University.

Holmes, C. D., 1947, Kames: AM. JOUR. SCI., v. 245, p. 240-249.

Johnston, W. A., and Wickenden, R. T. D., 1931, Moraines and glacial lakes in southern Saskatchewan and southern Alberta, Canada: Royal Soc. Canada, Trans., 3d ser., v. 25, sec. 4, p. 29-44.

Sharp, R. P., 1949, Studies of superglacial debris on valley glaciers: AM. JOUR. SCI., v. 247, p. 289-315.

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THERMAL CONDUCTIVITY AND MINERAL COMPOSITION OF SOME TRANSVAAL ROCKS

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ABSTRACT. The thermal conductivity and mineral composition of 42 samples of various rocks from the Transvaal are given. An attempt to correlate conductivity and composition shows qualitative rather than quantitative agreement for most samples. This is attributed to the complexity and degree of alteration of the rocks and in some cases to lack of data on the conductivity of monomineralic aggregates. Porosity is shown to be a dominating factor influencing the conductivity of some of the igneous rocks. Suggestions for further studies on the relation between mineral composition and conductivity are made.

INTRODUCTION

Although numerous measurements of the thermal conductivity of different rocks have been made and these results used for the solution of a variety of problems of geology and geophysics, the bulk of the published conductivity data is of no general use because full descriptions of the rocks have seldom been given. It is well established that rocks grouped together under a common geological name can have widely differing conductivity values.

Mean values of many of the conductivity measurements given in this paper have been used in conjunction with geothermal gradients to derive the rate of upward heat flow in the Earth's crust (Carte, 1954). The completion of petrographic examinations of thin sections of all specimens and X-ray analyses of some of them now enables detailed descriptions to be given, and an attempt to correlate mineral composition and thermal conductivity according to the theory that has been given by Birch and Clark (1940). This theory, which appears to have received scant practical application, assumes that the thermal resistivity of a rock comprised of randomly distributed and oriented crystals, small in comparison with the total heat flow path, is given by the series resistance of the various elements A, B, ...

$$\text{i.e. } R = x(A).R(A) + x(B).R(B) + \ldots\ldots\ldots \quad (1)$$

where x(A), x(B), ... are the proportions by volume and R(A), R(B), ... are the mean resistivities of A, B, ... respectively.

The following thermal conductivities of monomineralic aggregrates have been used, the bracketed figures being densities (Birch and Clark, 1940; Birch, 1954): quartz 0.0161 to 0.0171, plagioclase feldspars 0.0042, pyroxene 0.010, sericite 0.0042, chlorite 0.0125 (2.79), magnetite 0.0125 (4.6), biotite 0.010, calcite 0.0077 and dolomite 0.0106 (2.83).

The units of thermal conductivity, used throughout this paper, are gm-cal cm^{-1} sec^{-1} $degC.^{-1}$. Densities are expressed in gm/cc.

EXPERIMENTAL METHODS

Measurements of thermal conductivity were made in a divided-bar type of apparatus (Mossop and Gafner, 1951). Each determination involved measurements on three 1⅜-in. diameter disks of different thicknesses to minimize errors due to the effects of contact resistance. Absorption of the vaseline or glycerine and water film used to improve contact had a negligible effect on

the measured conductivity. The mean temperature of the determinations was always within a few degrees of 40°C. Although no evidence of thermal anisotropy has been found for any of the rock types given here, the specimens were always cut so that the heat flow in the apparatus was in the same direction as in situ. The few measurements of thermal diffusivity were found from the rate of change of temperature of one surface of a disk when the other was suddenly changed to and maintained at 0°C., the disk originally being uniform in temperature. The method gives the diffusivity ($cm^2\ sec^{-1}$) to within ten percent at a temperature of about 10°C. Densities are the mean of the ratio of mass to volume of each of the three disks. Unless otherwise stated, the three values did not differ by more than half a percent.

OBSERVATIONS

Source of specimens.—The specimens of dolomite, Witwatersrand quartzite and Ventersdorp lava all came from HB 15, a vertical borehole in the Klerksdorp district of the Transvaal. They were numbered with the depth in feet from which they were taken. Rocks from near Messina in the northern Transvaal are identified by the letter M; a number after M refers to the depth in borehole 0-32; small letters refer to specimens from a nearby copper mine. The Ongeluk and Stormberg lavas were taken from near Pretoria.

Dolomites.—Most of the specimens from the top section of HB 15 were almost pure dolomite, the grains being intimately interlocked and showing little variation in size in a given specimen. The average grain size shows a decrease with increasing depth. "Chert" (grains consisting of very fine-grained aggregates of quartz) and grains and veins of cryptocrystalline silica containing abundant black carbon grains are to be seen in some specimens.

TABLE 1

Granularity, Composition and Thermal Conductivity of Dolomites

	Grain size in mm			Approx. vol. percentage				
No.	Max.	Min.	Mean	Dolomite	"Chert"	Cryptocrystalline silica	Mean density	Thermal conductivity
100	1	0.05	0.3	95+	0	5	(2.83)	(0.0157)
300	0.8	0.05	0.3	95	Present	5	2.80	0.0120
500	1	0.05	0.4	95+	0	5-	2.84	0.0122
700	0.6	0.05	0.2	95-	5-	5-	2.81	(0.0119)
900	0.2	0.02	0.07	100	0	0	2.86	0.0124
1100	0.2	0.02	0.07	95+	0	5-	2.85	(0.0131)
1300	0.2	0.02	0.09	95+	0	5-	2.84	0.0115
1500	0.2	0.02	0.06	95+	0	5-	2.84	0.0103

The results of the petrographic examinations and thermal conductivities are given in table 1. Figures in brackets indicate uncertainty in the values given as the measurements on the three disks cut from the same specimen indicated a lack of uniformity. It is at once apparent that there is no relation between the wide spread of conductivities and the composition as given by examination of thin sections. It was suspected that the conductivity variations corresponded with variations in quartz content. That there are sections

of the core where the quartz content shows considerable variation within a short length was confirmed by quantitative X-ray analyses. As it was desired not to destroy the original specimens, the change of conductivity with quartz content was investigated by measuring the thermal diffusivity (α) of single disks and then crushing them up and finding the quartz content of a sample of the powder. As an example: two 1 cm-thick disks were cut from the remaining 6 in. length of core from 700 ft. The disk 700(d) is from the same end as the three original disks and 700(e) came from the remote end.

$$700(d) \text{ gave: } \alpha = 0.0243;\ \rho = 2.818;\ \text{quartz} = 11\%$$
$$k \text{ from equation (1)} = 0.0104$$
$$\text{and } 700(e): \alpha = 0.0277;\ \rho = 2.753;\ \text{quartz} = 39\%$$
$$k \text{ from equation (1)} = 0.0117$$

where ρ is density and k is conductivity. Assuming that the specific heat (c) of both samples is the same and equal to 0.175 gm-cal deg^{-1} at 10°C. we have

	700(e)	700(d)	Ratio
From α, k at 10°C.	0.0138	0.0125	
at 40°C.	0.0128	0.0115	1.11
From eqn. (1) k at 40°C.	0.0123	0.0110	1.12

which is probably better agreement than the data warrant. A point worth noting is that the quartz contents as derived from the density measurements, taking the density of quartz = 2.62 (see Quartzites below) and that of dolomite = 2.84, are 10 percent for 700(d) and 40 percent for 700(e).

Lavas.—The twelve specimens of Ventersdorp lava all consist of elongated crystals of feldspar and ferromagnesian minerals, such as pyroxene, amphibole and chlorite, in an interstitial groundmass of devitrified volcanic glass, often partly altered to a felt-like aggregate of feldspar, sericite, and chlorite. This aggregate is fine grained and the minerals in such a state of alteration that their detailed composition cannot be determined. The degree of alteration of the different minerals, their granularity, and the composition of the specimens vary to a large extent. Secondary calcite and quartz make their appearance in amygdales, veinlets and even as irregular patches in nos. 1700, 2300, 2500 and 3100. Results are given in table 2.

The spread of conductivity values for Ventersdorp lava is not large. The mean value of 0.0075 lies within a few percent of mean values obtained for several other boreholes—a valuable fact when it is desired to calculate heat flows in regions where there is Ventersdorp lava but no conductivity measurements have been made. The relation between conductivity and composition can be discussed in general terms only. The state of alteration of the minerals, the uncertainty of the composition of the interstitial aggregate, which includes minerals of widely divergent conductivities, and the lack of the conductivity of amphibole do not allow conclusions to be made as to the applicability of equation (1). The higher values are all for specimens having amygdales, high quartz content, or ones that are largely altered. The composition of the main body of 3100 is given as 70 percent feldspar and 30 percent devitrified glass and the conductivity is 0.0076. Examination of the disks showed that one edge

TABLE 2

Granularity, Composition and Thermal Conductivity of Ventersdorp Lava

	Alteration*	Feldspar Grain size	%	Pyroxene Grain size	%	Amphibole Grain size	%	Chlorite Grain size	%	Interstitial aggregate-devitrified glass Components**	%	Calcite Grain size	%	Quartz Grain size	%	Mean density	Thermal conductivity
1700	s	0.05 x 0.5	15		—		—		—	Slender lathlike crystallites of F, S, C and secondary calcite.	50	0.05	5	0.2	30	2.78	0.0083
1900	s	0.05 x 0.4	35		—	0.05 x 0.2	50	0.3	5	F, C, S	10	—	—	—	—	2.84	0.0081
2100	f	0.05 x 0.3	50		—	0.05	40	0.2	—	F, C, S	10	0.2	—	—	—	2.88	0.0062
2300	s	0.07 x 0.3	55			0.1	25	0.2	—	F, C, S	20	—	—	—	—	2.84	0.0075
2500	f	0.03 x 0.2	60	0.06 x 0.15	15	0.06 x 0.15	15	—	—	Opaque slightly devitrified glass	20	—	—	—	—	2.92	0.0077
2700	s	0.04 x 0.25	30			0.05	10	0.05	—	Very fine aggregate of F, S, C	60	—		0.1	—	2.85	0.0063
2900	s	0.05 x 0.2	45			0.1	15	0.2	—	F, S, C	40	1.0	In amygdales	0.5	In amygdales	2.80	0.0084
3100	s	0.01 x 0.1	70			—	—	0.03	—	C, S, E	30	0.1	—	—	—	2.77	0.0076
3300	f	0.05 x 0.3	40			0.05	10	0.05	—	C, S, E	50	—	—	—	—	2.86	0.0070
3500	s	0.03 x 0.2	50			0.05	10	0.05	—	C, S	40	—	—	—	—	2.92	0.0071
3700	l	—	20			0.05	30	0.05	—	C, S	50	—	—	—	—	2.92	0.0070
3900	l	0.1 x 0.5	50			—	—	0.5	—	C, S	40	0.1	10	—	—	2.79	0.0086
4100	l	—	55			—	—	0.1	—	S, C	45	—	—	—	—	2.79	0.0111

* Alteration to sericite:
slightly, s; fairly, f; largely, l.

** F, feldspar; S, sericite; C, chlorite; E, epidote.

Grain sizes are all expressed in mm.
% = percentage by volume.

No. 4100 had a veinlet of quartz and chlorite, mainly quartz.
X-rays gave quartz content = 36%.

amounting to about one-eighth of the total area was pure quartz. Treating the feldspar-glass and the quartz as two isolated conductors in parallel gives a low value for the computed conductivity (even if the devitrified glass is assumed to have a conductivity as high as that of quartz) indicating that the quartz probably has a bigger effect. No. 4100 came from a 200-ft. region of the borehole given in the geological log as dike. Its principal components are those of Ventersdorp lava. The petrographic examination showed a vein of quartz and chlorite, the quartz predominating. X-ray analysis gave the quartz content as 36 percent. This vein was observed to run through all three conductivity disks in a direction perpendicular to the plane surfaces. Assuming conductors of lava and quartz in the proportions of 64 and 36 percent respectively to be in parallel, the calculated conductivity is 0.0107, taking the lava conductivity as 0.0075.

Birch (1954) has suggested that the high conductivity of the non-amygdaloidal Ventersdorp lavas as compared with Michigan lavas (unaltered andesitic lava) is the result of extreme alteration. The petrographic examination of the Ventersdorp lava samples has certainly confirmed that they have undergone considerable alteration. To obtain further evidence on this point of discussion, samples of Stormberg and Ongeluk lava, which are from a geological series not nearly as old as the Ventersdorp lava, were collected. Unfortunately these samples showed as much alteration as the Ventersdorp lava. However, the dominant influence of porosity and the effect on conductivity of amygdales are clearly demonstrated. The Stormberg lava sample has an average grain size of 0.3 mm, feldspar (65%), and pyroxene (20%) being the main components. An interstitial brown material consisting of chlorite and magnetite is present (14%). The density is 2.7 and the measured conductivity is the exceedingly low value of 0.0034. The calculated value is 0.0052. The large difference must be attributed to porosity which is estimated from densities at 4 to 14 percent, depending on the amount of magnetite present. The one Ongeluk lava sample is a diabase consisting of plagioclase with an indefinite interstitial mass of chlorite and amphibole. According to a rough estimation, feldspar forms 50 to 60 percent of the rock. Its conductivity is 0.0070, density 2.80. The other sample is an amygdaloidal andesite consisting of feldspar laths, chlorite, and devitrified volcanic glass. The feldspar laths are approximately 0.1 mm in length. Accurate modal analysis is not possible but a rough estimation is: feldspar 20%, chlorite 50%, devitrified glass 30%. The quartz-filled amygdales occupy about one-tenth of the total volume and are two to six millimeters in diameter. The conductivity is 0.0091, density 2.78.

Quartzites.—The eleven samples of Witwatersrand quartzite consist mainly of quartz grains having a mean diameter of about 0.3 mm. Sericite replaces the quartz along the contacts of the grains. When this replacement is advanced the different grains seldom touch each other and are usually separated by a zone consisting of a fine-grained aggregate of sericite and quartz.

An interesting result in table 3 is that of 5618 which is practically pure crystalline quartz. The greatly differing principal conductivities of a quartz

TABLE 3

Granularity, Composition and Thermal Conductivity of Quartzites

Witwatersrand Quartzites

No.	Approx. composition from petrographic examinations (%) Quartz	Quartz-sericite aggregate	Mean grain size (mm)	"Chert"	Total quartz %	Mean density	Measured thermal conductivity	Computed thermal conductivity
6110	24	71	0.01	— (5% chlorite)	45	2.75	0.0101	0.0066
5910	40	60	0.02	—	61	2.72	.0099	.0077
6310					70	2.71	.0139	.0088
5120	68	32	0.01	—	81	2.67	.0125	.0106
5330	72	28	0.02 to 0.2	—	77	2.67	.0132	.0099
4930	78	22	0.02	trace	89	2.67	.0136	.0125
4730	82	18	0.01	—	83	2.67	.0137	.0110
6560	82	18	—	—	92	2.66	.0149	.0134
4530	83	15	0.01	2	90	2.67	.0139	.0128
5530	96	4	0.005	trace	97	2.64	.0140	.0152
5618	99	1	—	—	100	2.62	.0165	.0165

Quartzites from Messina

	Quartz	Feldspar	Altered biotite			
925	95	—	5	2.59	0.0137	—
1078	90	5	5	2.63	.0128	—

crystal lead to doubt as to the value that should be used for an aggregate. The two values for a quartz aggregate, 0.0161 and 0.0171, given in the introduction were computed from the expression given by Birch and Clark (1940) for (i) the reciprocal mean resistivity of a column of crystals oriented at random between the two isothermal surfaces and (ii) the mean conductivity of a single layer of randomly oriented crystals with heat flow perpendicular to the plane. As Birch and Clark have stated, the value for a rock aggregate probably lies between these two limits. This theory does not take into account imperfections in the packing of the crystals. As calculated from its density of 2.62, and 2.66 for a single crystal of quartz, the volume porosity of 5618 is 1.5 percent. Now, although the measured conductivity lies between the calculated limits, it seems likely that had the crystals been perfectly packed, the conductivity would have been considerably higher. The effect of the trace of impurity may also have the effect of lowering the conductivity rather more than might be expected. A second set of disks was cut from the remaining short length of core from 5618 ft. Unfortunately this length was not as uniform as the first; the densities of the disks varied from 2.626 to 2.634, and the spread in conductivities did not enable a reliable measurement to be made. With the present data the best value that can be used for a quartz aggregate is 0.0165.

The results in table 3 do show a relation between quartz content and conductivity. As the total quartz content of the Witwatersrand quartzite increases, and the density decreases, the conductivity shows a trend of increase. This is even more marked if the results are arranged in ascending order of "free" quartz as has been done in table 3. Despite this obvious relationship, the measured and computed conductivities do not agree at all well; but it cannot be concluded that equation (1) is necessarily at fault. It is to be seen that when the total quartz content is below about 90 percent the measured values are consistently higher than the computed ones. This is perhaps attributable to the rather more important role played by the quartz than that assumed of the simple "series" arrangement. The limited accuracy of the data combined with the unknown effects of packing and tiny cracks do not justify further conclusions. For example, it has been pointed out that there is some doubt as to the figure that should be used for the principal component, quartz. Also the conductivity of a pure sericite aggregate has never been determined experimentally: Birch and Clark assumed that sericite would resemble the feldspars with respect to conductivity. Improved agreement between measured and calculated conductivities would follow if 0.006 was used instead of 0.0042.

Grain size may well be another influencing factor. A careful examination of 5330 and 5120 showed no reason why the conductivity of 5120, which has the slightly greater quartz content of the two, should be lower except that its interstitial aggregate is not as coarse as that of 5330. The low conductivity of 5530 relative to 5618 cannot be brought about by the small amount of sericite present: porosity is probably the answer. Before leaving the Witwatersrand quartzites, it might be mentioned that the formula given by Bullard (1939) relating the conductivity and quartz content of eight samples of feldspathic and chloritoid Witwatersrand quartzites does not fit the above results; also, it gives an unlikely value for 100 percent quartz.

The two quartzites from Messina have as their main component strained quartz in grains varying between 2 and 5 mm. Biotite, nearly completely altered to magnetite, chlorite, and sericite, is present. Plagioclase feldspar is present in 1078. The cracked appearance of these two samples, especially 925, would suggest that porosity accounts for the low measured conductivities relative to the Witwatersrand quartzites and to the computed values.

Dolerites, granite and syenite.—Two samples of dolerite dike were obtained from Messina. M692 contains approximately 70 percent plagioclase feldspar (labradorite), 20 percent pyroxene (pigeonite), and less than 10 percent ilmenite. A small amount of micropegmatite (intimate intergrowth of feldspar and quartz) is present. The density is 2.84, measured conductivity 0.0052 and the computed value will be very close to this unless ilmenite has an exceptionally high or low conductivity. M(e) consists of plagioclase feldspar, pyroxene, chlorite and an unusually large amount of magnetite. The average grain size is approximately 0.3 mm although the feldspar crystals reach lengths of 1 mm. It is well suited for a modal analysis and the error of the following percentage composition is of the order of only one percent:

feldspar 60, pyroxene 19, magnetite 10, and chlorite 11. The magnetite brings the bulk density up to 2.91. The porosity as found from the bulk density and the densities of the component minerals is about 5 percent, a fairly high value for igneous rocks. This factor may account for the differences between the measured and computed conductivities which are 0.0050 and 0.0056 respectively.

The two granites M425 and M789 consist mainly of alkali feldspars (orthoclase and albite), slightly altered to sericite, with quartz and biotite, the latter largely altered to magnetite, sericite, and chlorite. The grain sizes vary from less than 1 mm to more than 5 mm. Garnet is present in M425. M(a) is a syenite consisting of feldspar, chlorite, and garnet. The feldspar is mainly orthoclase which shows extensive alteration to sericite. Plagioclase is present in smaller amounts. Two types of chlorite were recognized: a dark green variety, probably an alteration product of biotite and a light green type, which is an alteration product of garnet. Relicts of garnet are present within the latter type. The grain sizes vary between 1 and 2 mm. Table 4 gives the composition and conductivity of these three samples. Calculated conductivities given in brackets are uncertain because of lack of data on garnet and altered biotite.

TABLE 4

Composition and Thermal Conductivity of Granites and Syenite

	M425	M789	M(a)
Feldspar	40	90	68
Quartz	40	—	—
Garnet	10	—	2
Altered biotite	10	10	—
Chlorite	—	—	30
Density	2.59	2.62	2.70
Conductivity	0.0070	0.0048	0.0062
Calc. cond	(0.006 to 0.008)	(0.0049)	0.0053

DISCUSSION

Before the composition as determined from a petrographic examination can be used in any calculation of conductivity, the specimen must be examined critically with a view to deciding whether a thin section is likely to be representative of the whole mass. Where no obvious heterogeneities such as amygdales or cracks exist, density measurements on several samples can often furnish information on the uniformity. There is no doubt that the thermal conductivity of a rock aggregate is a function of the component minerals. Some of the results given in this paper and results of Birch and Clark show that when the grain size is small with respect to the heat flow path the relationship is expressed by the series resistance of the various elements. Even in igneous rocks porosity can exert a dominating influence on the conductivity. Unless this effect is taken into consideration there will be some rocks for which an unexpectedly large difference between calculated and measured conductivities is found.

The complexity and degree of alteration of the majority of the rock samples for which results are given in this paper make them unsuitable for an attempt to correlate conductivity and composition. A study of less complex materials specially selected for the purpose would be advisable. Bushveld rocks, which vary in composition from practically pure anorthosites through gabbros and norites to pyroxenites, would be most suitable. More information on single crystals and monomineralic aggregates is essential. In particular, further investigations on the feldspars would be valuable. They are the poorest conductors and have shown an increase of conductivity with increasing temperature contrary to other crystalline aggregates.

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REFERENCES

Birch, Francis, 1954, Thermal conductivity, climatic variation, and heat flow near Calumet, Michigan: Am. Jour. Sci., v. 252, p. 1-25.

Birch, Francis, and Clark, Harry, 1940, The thermal conductivity of rocks and its dependence upon temperature and composition: Am. Jour. Sci., v. 238, p. 529-558, 613-635.

Bullard, E. C., 1939, Heat flow in South Africa: Royal Soc. London Proc., ser. A, v. 173, p. 474-502.

Carte, A. E., 1954, Heat flow in the Transvaal and Orange Free State: Phys. Soc., Proc., B, v. 67, p. 664-672.

Mossop, S. C., and Gafner, G., 1951, The thermal constants of some rocks from the Orange Free State: Chem., Met. Min. Soc. South Africa Jour., v. 52, p. 61-73.

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REVIEWS

The Itinerant Ivory Tower, Scientific and Literary Essays; by G. E. HUTCHINSON. P. xi, 261; 6 figs., frontispiece. New Haven, 1953 (Yale University Press, $4.00).—It is rare, in this age of specialization, to be allowed to witness the wandering of a scientific mind in fields outside the owner's specialty. Hutchinson's book permits this privilege. Many of the essays here collected have appeared in his column "Marginalia" in *The American Scientist*, others have appeared elsewhere. "The Dome," on Rebecca West, is here published for the first time. But the virtue of the book is the unity which results from collecting these very diverse essays into a single volume. Hutchinson's mind, his epistemology, is deeply dualistic. He sees the universe as integrated—i.e. as potentially understandable—in both esthetic and scientific terms. His special field is freshwater ecology, but he seeks for coherence and beauty in every field ranging from the natural history of *Peromyscus* to the functions of a university. He appropriately illustrates an essay on D'Arcy Thompson's work on the dynamics of growth with a lyric passage from Rebecca West's "The Strange Necessity" in which that writer expresses the pleasure of perceiving in a girl's posture the same dynamics as those of the Forth Bridge in the background.

The keynote of the book is Hutchinson's insistence upon the pleasure of scientific perception. This reviewer would recommend this book to students and to teachers as a way of telling both what scientific education might be.

GREGORY BATESON

How to Know the Minerals and Rocks; by RICHARD M. PEARL. P. 192; 156 drawings, 46 color photographs. New York, 1955 (McGraw-Hill Book Co., Inc., $3.50).—This simplified descriptive work on identification of minerals and rocks fills a need long felt by beginning collectors of natural objects. It includes brief chapters on origin of minerals and rocks, forming a mineral collection, "keys" (i.e. diagnostic criteria) for the recognition of minerals and rocks (e.g. luster, hardness, etc., of minerals; textures, minerals, etc., of rocks). Systematic descriptions are arranged to enable a beginner to identify most of the 127 minerals and 22 rocks described. The color plates are moderately successful—we find orange cinnabar and rhodochrosite; dark blue beryl and azure-blue malachite; green franklinite, stibnite and hematite; gypsum that is more golden than gold; light blue microcline; and pink limonite; but most of the others are reasonably near their usual colors. Four of the best color plates appear only on the jacket, and without identification. To picture handsome specimens in full color is a very difficult problem indeed. Even the best color transparencies leave much to be desired in many instances, and to secure printed reproductions of any at all at such a moderate cost is a considerable achievement. Many collectors will welcome this book.

HORACE WINCHELL

Structural Geology, 2d ed.; by MARLAND P. BILLINGS. P. xiv, 514; 381 figs., 21 pls. New York, 1954 (Prentice-Hall, Inc., $6.75).—The first edition of this useful textbook, published in 1942, became widely known. Revision now takes account of the author's cumulative experience, of constructive sug-

gestions from other instructors, and of recent developments in the subject. The general scope of the treatment remains unchanged; the aim is to present and explain facts and principles relating to geologic structure and does not extend to the broad concepts and theories of world tectonics. This restriction of subject matter seems wise. Beginners should be given all possible basic equipment before they are introduced to the more complex problems on the frontiers of the field.

Extensive revision has greatly improved the book, with only moderate increase in size. The new volume has four more chapters and about fifty figures more than the old, but these changes were effected largely by reorganization and substitution. This kind of treatment is evident in the early chapter "Mechanical Principles," which is much more effective though no longer than the original. Titles of new chapters are "Mechanics of Faulting," "Strike-Slip Faults," "Causes of Folding and Faulting" (a limited glance at tectonic theory), and "Lineation." A chapter "Emplacement of Large Plutons" replaces and modifies the old chapter "Granite Tectonics." Laboratory exercises are increased in number, and exercise sheets for certain problems are included in a pocket, not printed on detachable pages as in the earlier edition.

Perhaps the most conspicuous change in the book has to do with the concept of the strain ellipsoid. In the first edition the author noted and apparently accepted arguments against the once-popular analysis that identified the theoretical planes of no distortion with actual planes of failure under shearing stress. Nevertheless many diagrams in the earlier book show the "strain ellipse" with traces of conjugate shear planes presenting a large obtuse angle in the direction of maximum compression. Students were confused by this evident inconsistency, which is eliminated in the revision. Concepts of stress and strain ellipsoids are discussed briefly in the chapter "Failure by Rupture," and limited use of the concepts is recommended. Absence of the "strain ellipse" from nearly all diagrams illustrating cleavage and schistosity is conspicuous and, in the judgment of this reviewer, commendable.

Some controversial subjects are difficult to treat within the limited space available in a textbook. Preferences in exact definition of common terms will doubtless persist, and the author of *Structural Geology* recognizes this as a problem, though not of major rank. In a chapter heading he uses *gravity* and *normal* faults as synonyms, probably with the thought of harmonizing two usages though he recognizes differences in strict definitions of the terms. His own definition of a *nappe* as "a large body of rock that has moved forward more than one mile from its original position" gives proper emphasis to a limiting scale, though another author has proposed as the lower limit the much larger figure 5 km. A far more serious matter is the presentation of rock cleavage and schistosity, a subject still in a state of flux, with schools of thought widely separated. Billings notes these differences, and gives a reasonably balanced discussion that brings out the unresolved problems. A large merit of the new edition is its representation of structural geology as a field for continued discovery rather than a subject in which we have all the answers.

CHESTER R. LONGWELL

Los Yacimientos Minerales de Bolivia; by FEDERICO AHLFELD. P. 277; 100 figs., colored map. Bilbao, Spain, 1954 (Imprenta Industrial S. A., Alameda de Mazarredo, 57-59).—This book is a revision of a similar volume written by Ahlfeld in 1941 and now out of print. Short sections are devoted to the geomorphology and geology of Bolivia. The remainder of the book consists of brief descriptions of the mineralogy and structure of all the important Bolivian mineral deposits and of the history of development. An excellent index map and a list of selected references are included as an appendix. Accompanying the book is a map showing the location of 350 mining districts and deposits.

Unfortunately, the hypotheses of origin for each deposit are not presented. Ahlfeld notes in his discussion of the tin deposits, for example, that the study of the Bolivian tin deposits led to important revisions of older hypotheses on the pneumatolytic origin of tin. Yet in the four-page section on Potosi no summation of the hypotheses of origin for the Potosi tin ores is presented, and no discussion of the genetic implications of the unusual mineralogy is given.

The book does not contain the detail found in similar volumes such as *Geology of Australian Ore Deposits* (1953, Australasian Institute of Mining and Metallurgy, Melbourne), but it should serve as a good general reference. The author's comment in the preface on the persistent refusal of the Bolivian government to provide for an adequate geological survey in spite of the country's overwhelming dependence on mineral resources helps to explain why such a book cannot present more detailed information.

LAWRENCE LUNDGREN

Gulf of Mexico, Its Origin, Waters, and Marine Life; coordinated by PAUL S. GALTSOFF. U. S. Fish and Wildlife Service Fishery Bulletin 89. P. xiv, 604; 74 figs. Washington, 1954 (U. S. Government Printing Office, $3.25).—Here is an excellent source of existing data, and a necessary starting point for any investigations in the Gulf of Mexico.

The preface to this volume states that its purpose is " . . . to summarize in a convenient form the present knowledge about the Gulf of Mexico." Even in a region which in the past has received perhaps less than its fair share of attention, the compilation of such varied factual information so widely scattered is a formidable task. Certainly then the coordinator, Paul S. Galtsoff, deserves congratulations for assembling the contributions of 55 specialists in only three years.

The work is divided into twenty chapters which may be grouped as follows:

History of explorations—Chapter I	29 p.
Geology (shorelines, structure, topography, and sediments)—Chapter II	43 p.
Marine Meteorology, Physics, and Chemistry (tides, currents, illumination, chemical composition, atmospheric circulation) —Chapters III, IV	60 p.

Plant and Animal Communities (plankton, algae, flowering plants, and animals)—Chapter V	50 p.
Biology (Bacteria, fungi, unicellular algae, all the invertebrate phyla, fishes, turtles, birds, and mammals)—Chapters VI-XIX	333 p.
Pollution—Chapter XX	19 p.

Quite naturally the contributions vary considerably in their coverage, depending mainly on the amount of information available. In many cases the data are so limited that only a very general summary can be given, but in a few cases such as tides and certain groups of plants and animals in parts of the Gulf there is sufficient information for a relatively comprehensive treatment. Each of the 71 contributions has a bibliography which is complete to 1950. The 28-page index will considerably increase the usefulness of the work because it includes a good breakdown of topic headings as well as species and author listings.

The lead chapter is a fine summary of the history of explorations in the Gulf from the Spanish adventurers to modern oceanographic expeditions. It has several reproductions of interesting early charts of the Gulf.

The chapter on geology consists of a 24-page paper on shorelines by W. Armstrong Price, and a 16-page paper on structure, morphology, history, and modern bottom deposits by S. Y. Lynch. Price divides the Gulf coasts into (1) alluvial coasts, (2) drowned limestone plateaus, (3) young orogenic coasts, and (4) biogeneous development on various coasts including coral reefs and mangroves. Submergence and emergence, although recognized, are considered less valuable for classification. The paper on structure, morphology, and sediments is a clear summary of existing data, and it discusses historically such problems as the origin of the Gulf basin, the existence of a Gulf Coast geosyncline, and the formation of continental shelves and slopes in the Gulf. The discussion of sediments and the generalized distribution pattern gives a good resumé of earlier work. However, the rate of accumulation of sediment data has so accelerated recently that, even as this summary was being written and published, hundreds of cores were being taken by several groups all over the Gulf. The enormous impetus given to marine geologic studies by the offshore oil discoveries and the current emphasis on paleo-environmental interpretations has already been felt, and this new data will certainly help to fill the gaps brought out in this summary of the status of knowledge.

The papers in the chapters on Marine Meteorology, Physics, and Chemistry provide good summaries of scanty data and give an introduction to some of the problems in each field. They also serve to indicate what sort of future work is needed. The late H. A. Marmer was able to use the extensive tide and sea level data from the Gulf to prepare an excellent basic discussion of tides and sea level fluctuations.

The chapter on plant and animal communities treats in separate articles phytoplankton, zooplankton, algae, flowering plants, and sessile invertebrates. Only for the algae and flowering plants of Florida and for the oyster communities of the Northern Gulf are there sufficient data to give more than a general idea of the associations. Here again, as with bottom sediments, re-

cently published work and investigations now in progress will provide important new data on the animal communities in shallow water.

More than half of the volume is devoted to Biology. The individual contributions range from less than two pages on sponges and on bryozoans to a 27-page treatment of holothurians including new keys and species descriptions. For the relatively abundant and well-studied animals, there are usually enough data for some discussion of ecology, distribution, and in some cases habits.

The availability of such an enormous amount of concentrated information far outweighs objections by specialists to certain classifications and interpretations. It is, however, unfortunate that there is no general article which discusses some of the peculiarities of the Gulf and compares it with the Mediterranean Sea and other regions. Such an article might also have stimulated needed work in certain areas. Perhaps the appearance of this work will encourage such a synthesis? ROBERT N. GINSBURG

An Introduction to Ornithology; by GEORGE J. WALLACE. P. xii, 443; 180 figs. New York, 1955 (The Macmillan Company, $8.00).—The author has presented a well-written textbook for beginning students of ornithology. It affords a comprehensive account of the main contemporary studies, superimposed on the usual morphological and developmental aspects of birds. After an introductory history of ornithology and a brief phylogeny of the vertebrates, the external and internal avian anatomy is discussed with somewhat more emphasis on the integumentary system than on any other. The main ecological characteristics of birds are treated as parts of their annual cycle, with territory-formation and nesting, brood incubation and rearing, dispersal and migration considered in their seasonal sequence; Wallace has succeeded in an attempt to interrelate behavioral, physiological and morphological systems to the above cycles. The first part of the text is concluded in a section devoted to the economic importance and management of birds.

For the semester course, a second part has been added, which treats in detail the fossil history and modern classification. This is followed by separate chapters on laboratory methods and the ornithological literature; together, these latter chapters form a welcome innovation in textbooks for beginning students.

While this volume will fill a long-felt need for a general text in ornithology, it is not without some faults. The extensive and up-to-date bibliography is awkward to use, because the references in the text may be found either at the ends of chapters or in a terminal list of citations. It would be desirable to have had included a sufficient author index, with which one could find all references to a single author without a time-consuming search of the listed references at most chapter endings and the major bibliography. The citations and text reveal a notable omission of the contributions of European ornithologists; the works of investigators like Matthews, Delacour, Stresemann, Lorenz and Tinbergen, if cited, are hardly considered within the framework of the discussions to the extent that their ideas and findings warrant.

The format of the book is attractive. This has been accomplished through a profusion of black-and-white photographs and line drawings, each of which has been well chosen and reproduced. The text is clear, and there is a consistent attempt to indicate unfamiliar terms in bold-face type, accompanied by precise definitions.

Considered as a whole, the book can well be used as a central nucleus for ornithology courses. WILLIAM B. COTTER

Publications Recently Received

U. S. Geological Survey Water-Supply Papers: 1225, Water Levels and Artesian Pressures in Observation Wells in the United States in 1952, Pt. 5, Northwestern States ($ .60). 1239, Surface Water Supply of the United States, 1952, Pt. 6-A, Missouri River Basin above Sioux City, Iowa ($1.50). 1260-A, Floods of September 1952 in the Colorado and Guadelupe River Basins, Central Texas; by S. D. Breeding and J. H. Montgomery ($ .45). 1264, Quality of Surface Waters for Irrigation, Western United States, 1951 ($1.00). 1299, The Industrial Utility of Public Water Supplies in the United States, 1952, Pt. 1, States East of the Mississippi River; by E. W. Lohr and S. K. Love ($2.25). 1300, Pt. 2, States West of the Mississippi River; by E. W. Lohr and S. K. Love ($1.75). Washington, 1954 and 1955.

U. S. Geological Survey Bulletins: 989-D, Geology of the Eastern Part of the Alaska Range and Adjacent Area; by F. H. Moffit ($1.25). 990, Geology and Oil Resources of the Jonesville District, Lee County, Virginia; by R. L. Miller and W. P. Brosge ($2.75). 996-D, Hawaiian Volcanoes During 1951; by G. A. Macdonald and C. K. Wentworth ($ .35). 1015-A, Fluorspar Deposits near Meyers Cove, Lemhi County, Idaho; by D. C. Cox ($1.25). 1015-B, Niobium (Columbium and Titanium at Magnet Cove and Potash Sulphur Springs, Arkansas; by V. C. Fryklund, Jr., R. S. Harner, and E. P. Kaiser ($ .35). 1019-B, Bibliography of U. S. Geological Survey Trace Elements and Related Reports to June 1, 1954; by J. H. Wallace and H. B. Smith ($ .30). Washington, 1954 and 1955.

U. S. Geological Survey Professional Papers: 260-A, Geology of Bikini and Nearby Atolls, Pt. 1, Geology; by K. O. Emery, J. I. Tracey, Jr., and H. S. Ladd. 264-D, An Appraisal of the Great Basin Middle Cambrian Trilobites Described Before 1900; by A. R. Palmer ($1.00). Washington, 1954.

Cells and Societies; by J. T. Bonner. Princeton, New Jersey, 1955 (Princeton University Press, $4.50).

Louisiana Geological Survey Bulletin 29: Geology of Webster Parish; by J. L. Martin et al. Water Resources Pamphlet 1: An Analysis of Contour Maps of Water Levels in Wells in Southwestern Louisiana, 1952 and 1953; by S. W. Fader. Baton Rouge, 1954.

Arachnoidea from South Georgia and the Crozet Islands with Remarks on the Subfamily Masoninae; by Hans Tambs-Lyche. Scientific Results of the Norwegian Antarctic Expeditions 1927-1928 et sqq. no. 35. Oslo, 1954 (Det Norske Videnskaps-Akademii Oslo).

Introduction to Physical Geology; by C. R. Longwell and R. F. Flint. New York, 1955 (John Wiley & Sons, $4.95).

Coals and Bitumens; by S. I. Tomkieff. London, 1954 (Pergamon Press, Ltd., 17 *s* 6 *d*).

The Elements of Chromatography; by T. I. Williams. New York, 1955 (Philosophical Library, $3.75).

Down to Earth; by Robin Place. New York, 1955 (Philosophical Library, $7.50).

Preliminary Report on Coated Lightweight Concrete Aggregate from Canadian Clays and Shales, Pt. 6, British Columbia; by H. S. Wilson. Canada Dept. Mines Memorandum Series 128. Ottawa, 1954 ($ .50).

ERRATUM

By a printer's error, line 1 on page 251, in Richard Foster Flint's paper entitled "Rates of Advance and Retreat of the Margin of the Late-Wisconsin Ice Sheet" in the May 1955 issue of the American Journal of Science, was omitted in the final printing. This page should begin: Retreat from the outer limit of advance in Ohio began less than 18,000 C^{14} yr. ago.

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